V2V Safety Communications Scalability

- Preliminary observations from the 200 vehicle test scenarios:
  - The channel congestion level was highest for the Baseline 10 Hz configuration but was not to the point of being fully saturated
  - For all configurations and scenarios, there was no evidence of significant degradation of the communication performance that would seem to result in degradation of the vehicle safety applications for 200 vehicles
  - Algorithm X and Algorithm Y show promising communication performance that may result in good performance of the vehicle safety applications for 200 vehicles while reducing the channel utilization to lower values in comparison to the baseline 10 Hz configuration
- Next Steps – Finalize V2V safety communication technique(s) that will support large-scale deployment level of vehicles while preserving the performance of V2V safety applications (Phase II)
  - Calibration of communication simulation environments
  - Algorithm refinement and, if necessary, development of alternate approaches
  - Field testing
  - Incorporate recommendations into standards

Security Management

- Task Goal
  - Develop technical requirements and build a prototype security system, test this system, and utilize it within the scalability testing
- Accomplishments:
  - Developed enhanced OBE security software, a prototype infrastructure security server, and Security Framework Access Devices (SFADs)
  - Equipped 4 OBEs (2 each from two suppliers) with the enhanced security software and provisioned them with SFADs to communicate with the CAMP VSC3 prototype security server
  - Tested the OBEs in the scalability environment at TRC in close proximity with 196 other units broadcasting BSMs on channel 172
  - Demonstrated that the OBEs were able to request and receive security credentials from the Registration Authority (RA) located in the CAMP VSC3 lab, receive batches of certificates, and verify certificates from other OBEs for the following channel configurations:
    - Channel 174 (adjacent channel to the other 196 units)
    - Channel 172 (same as 196 units)
    - Cellular 3G

DATA INTEGRITY AND RELIABILITY CERTIFICATION

- Goal:
  - Define and assess the requirements necessary for vehicles to trust the accuracy of the data in the OTA messages and to ensure proper functionality of the safety applications
- Accomplishments:
  - Developed the SP BSM Minimum Performance Requirements
  - Developed initial draft of objective test procedures and test plan for:
    - Vehicle Awareness Device (VAD) / Aftermarket Safety Device (ASD) Minimum Performance Requirements (MPR) certification for MD
    - ASD application certification for MD
  - Determined differences in the outcome of the preliminary objective tests when the sensor data are varied within the currently expected accuracy ranges using simulation
  - Assessed aftermarket units (with no, or limited, connection with vehicle networks) in terms of capabilities and ability to meet preliminary certification procedures
  - Follow-up work is being conducted in V2V-MD Project

COORDINATION W/ OTHER USDOT PROGRAMS

- For Standards Development
  - Active participation in IEEE 802.11, IEEE 1609.x, and SAE J2735
  - Well-positioned for SAE J2945 development
- For Safety Pilot Model Deployment (SPMD)
  - Knowledge transfer of preliminary technical requirements from V2V-Interoperability research for consideration in USDOT SPMD activities
  - Coordination subsequently transferred to CAMP VSC3 V2V-MD Project
- With Vehicle Infrastructure Integration Consortium (VIIC)
  - Security technical inputs related to security policy considerations
  - Close coordination for initial deployment model identification activities
  - Technical cooperation on EU-US harmonization
- For US-EU Standards Harmonization
  - Basic Safety Message (BSM) / Cooperative Awareness Message (CAM) harmonization at the data element level
  - Harmonization on minimum performance requirements on hold pending further input from V2V-MD Project

Appendix XXX. João Almeida et al., *Mitigating Adjacent Channel Interference in Vehicular Communications Systems*, DIGITAL COMMUNICATIONS AND NETWORKS (May 2016).

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Mitigating adjacent channel interference in vehicular communication systems

João Almeida [a,b,*], Muhammad Alam [a], Joaquim Ferreira [a,c], Arnaldo S.R. Oliveira [a,b]

[a] *Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*
[b] *DETI - Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal*
[c] *ESTGA - Universidade de Aveiro, 3754-909 Águeda, Portugal*

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ABSTRACT

In the last few decades, dedicated wireless channels were specifically allocated to enable the development and implementation of vehicular communication systems. The two main protocol stacks, the WAVE standards proposed by the IEEE in the United States and the ETSI ITS-G5 in Europe, reserved 10 MHz wide channels in the 5.9 GHz spectrum band. Despite the exclusive use of these frequencies for vehicular communication purposes, there are still cross channel interference problems that have been widely reported in the literature. In order to mitigate these issues, this paper presents the design of a two-stage FIR low-pass filter, targeting the integration with a digital baseband receiver chain of a custom vehicular communications platform. The filter was tested, evaluated and optimized, with the simulation results proving the effectiveness of the proposed method and the low delay introduced in the overall operation of the receiver chain.

1. Introduction

Vehicular communications play a key role in the development of Intelligent Transportation Systems (ITS), whose main goal is the improvement of road safety and traffic efficiency. By extending the driver's field of view, vehicular networks can increase the time available to make decisions or to react in the case of traffic hazards. This way for instance, collisions in low visibility intersections and chain reaction crashes can be drastically reduced. In addition to this, value-added infotainment services can also be provided by vehicular communication systems, such as broadband internet connection or prices and locations of parking slots or gas stations.

There are two main protocol stacks for vehicular communications systems [1], enabling exchange of data among vehicles (V2V communications) and between vehicles and the road-side infrastructure (V2I/I2V). These two families of standards correspond to the IEEE Wireless Access in Vehicular Environments (WAVE), adopted in the United States, and the ETSI ITS-G5 in Europe. At the physical and medium access control layers, both protocol stacks rely on the IEEE 802.11p standard, an amendment to the IEEE 802.11 Wi-Fi reference [2]. In comparison with the typical Wi-Fi operation, there are just a number of modifications that are introduced to enhance the behavior of the communicating nodes under such dynamic scenarios. For instance, the channel bandwidth is reduced from 20 MHz to 10 MHz, in order to mitigate the effects of multi-path propagation and Doppler shift. As a consequence, the data rate is half of what can be obtained with standard Wi-Fi, i.e., from 3 Mbit/s to 27 Mbit/s instead of 6–54 Mbit/s. Another example is the introduction of non-IP messages that are broadcast outside the context of a Basic Service Set (BSS), avoiding the overhead introduced by the registration and authentication procedures, commonly present in wireless local area networks.

In order to guarantee that vehicular communications do not suffer from any type of interference from unlicensed devices, the Federal Communications Commission (FCC) in the United States and the European Conference of Postal and Telecommunications Administrations (CEPT) in Europe, allocated a dedicated spectrum band at 5.9 GHz (Fig. 1). In America, a bandwidth of 75 MHz was reserved, while in Europe only 50 MHz were assigned. This spectrum was divided into smaller 10 MHz wide channels and in the American case, a 5 MHz guard band at the low end was also included. As a result, there are 7 different channels for IEEE WAVE operation and 5 for the case of ETSI ITS-G5. In Europe, 30 MHz (3 channels) are reserved for road safety in the ITS-G5A band and 20 MHz are assigned for general purpose ITS services in the

* Corresponding author at: Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal.
E-mail addresses: jmpa@ua.pt (J. Almeida), alam@av.it.pt (M. Alam), jjcf@ua.pt (J. Ferreira), arnaldo.oliveira@ua.pt (A.S.R. Oliveira).
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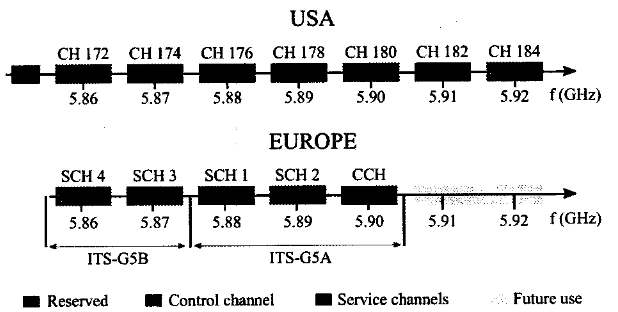

Fig. 1. Spectrum allocation for vehicular communications (adapted from [1]).

ITS-G5B band. As a general rule, a control channel (CCH 178 in the USA and CCH 180 in Europe) is exclusively used for cooperative road safety and control information. The remaining channels are designated as Service Channels (SCH). In the United States, concerns about the reduced capacity for road safety messages led to the decision to allocate SCH 172 specifically for applications regarding public safety of life and property [3]. Moreover, it is mandatory in Europe to have two radios in each vehicular communication platform, in order to guarantee at least one radio always tuned in the dedicated safety channel [4].

Notwithstanding the decision to allocate specific wireless channels for vehicular communication purposes, there are still issues with the operation of these systems, caused by the cross channel interference in the IEEE-WAVE/ETSI-ITS-G5 band and with the European tolling systems operating in the 5.8 GHz frequency band. The interference risks in the latter case were early identified by CEPT in 2007 [5] and several studies [6–8], simulation and experimental tests [9] were then conducted in order to evaluate the impact of ITS-G5 communications in a coexistence scenario with Electronic Toll Collection (ETC) systems. In these tests [9] organized by ETSI, the results have shown that under certain conditions, the ITS-G5 signals can harmfully interfere with ETC systems, causing a loss or non-completion of ETC transactions and/or a disruption of the stand-by mode of ETC On-Board Units (OBUs), i.e. the devices placed inside the vehicles.

Based on these findings, it was clear that the simultaneous operation of both systems at toll plazas could be seriously disturbed. This could lead to safety and congestion problems in these areas and cause substantial loss of revenues for road operators. It was also concluded that this interference is inevitable, unless ITS-G5 will adapt the transmitted power within a certain range around the tolling station or reduce the duty cycle of the message transmission. As a result, ETSI has introduced mandatory requirements for ITS-G5 stations to switch to a "protected mode" [7]. This shall be done when receiving information from any other ITS station containing the location of a tolling station. The ITS station that sends out the information about the tolling station location may either be a fixed located transmitter – Road-Side Unit (RSU) – in the vicinity of the tolling station, or it may also be an OBU in any vehicle that, in addition, is equipped with a 5.8 GHz toll detector.

Furthermore, there is also a perspective to use IEEE 802.11p for ETC communications, but studies [10] have shown it is possible that 802.11a based on-board devices operating in the 5 GHz band could degrade the performance of ETC systems based on vehicular communications. Simulation and real-world experiments [10] demonstrated an increase in the Packet Error Rate (PER) of the ETC 802.11p based system, when both technologies were working simultaneously. It was also shown that this effect cannot be removed by simply increasing the power transmitted by the 802.11p ETC units. In general, one can conclude that wireless communication systems operating near the 5.9 GHz frequency band pose serious problems to the performance of vehicular networks.

Nevertheless, the major source of interference in vehicular communications systems is the cross channel interference, generated by nodes communicating in the adjacent channels [11]. This Adjacent Channel Interference (ACI) can severely compromise the integrity of the messages received by a radio unit, whenever simultaneous communications occur in the nearby channels. Therefore, in order to reduce the effect of ACI in vehicular communication radio links, this paper presents the design of a two-stage Finite Impulse Response (FIR) filter, which guarantees an efficient suppression of the unwanted components of the received signal. At the same time, it is also ensured that few digital hardware resources are utilized and only a small delay is introduced in the receiver chain of the ITS-G5 station. The rest of the paper is organized as follows. Section 2 presents some related work and background on the topic of ACI in vehicular networks. Section 3 shows the effects of cross channel interference in the received signal of a custom vehicular communication platform, while Section 4 describes the design of the proposed digital filter and presents the obtained simulation results. Finally, Section 5 summarizes the concluding remarks and discusses some future work.

2. Related work and background

The IEEE WAVE and ETSI ITS-G5 protocol stacks establish a multi-channel architecture for vehicular communications, where different vehicles in the same geographical area can simultaneously transmit over the multiple channels presented in Fig. 1. This design decision produces obvious throughput improvements, however, since the parallel usage of adjacent channels can occur when vehicles are in the radio range of each other, interference between different nodes' transmissions may arise. This adjacent channel interference (ACI) can cause two main negative effects in the network communications [11]: an increased PER and a reduced transmission opportunity. In the former case, the Signal-to-Interference-plus-Noise-Ratio (SINR) of a packet being received by a node can be increased by another unit communicating in an adjacent channel, which may lead to the impossibility of correctly processing and decoding the frame. This will cause the loss of the packet and, if the situation is not momentary, it can result in large values of PER. The second mentioned effect occurs when a node wants to transmit a frame, but it perceives the channel as occupied due to a packet transmission in an adjacent channel. This channel busy indication is given by the Clear Channel Assessment (CCA) mechanism, being triggered by the power level sensed in the wireless medium, raised by the interferer in the nearby channel. In this situation, the potential transmitter will follow the back-off procedure specified by the CSMA method of IEEE 802.11 standard and thus the access to the wireless medium and the transmission of the intended message will be deferred. Moreover, it can happen that the packet decoding process in the potential receivers is not affected by the interferer, but the transmitter is still wrongly prevented to send its message. The ACI problem could be amplified in dual-radio units, as the ones in Europe, with antennas simultaneously operating on nearby channels and located in the same place, either in the same vehicle or road-side site.

In order to limit cross channel interference, the standard [2] specifies a spectrum emission mask that defines the out-of-band energy allowed for a transmitting device. This spectral mask is defined up to 15 MHz far from the center frequency and it becomes more stringent and difficult to comply with higher transmission power classes (A–D) [12]. On the receiver side, the standardization rules also establish a minimum Adjacent Channel Rejection (ACR) ratio for each modulation, measured by the power difference between the interfering signal and the signal in the desired channel. These masks are sufficient to avoid the most

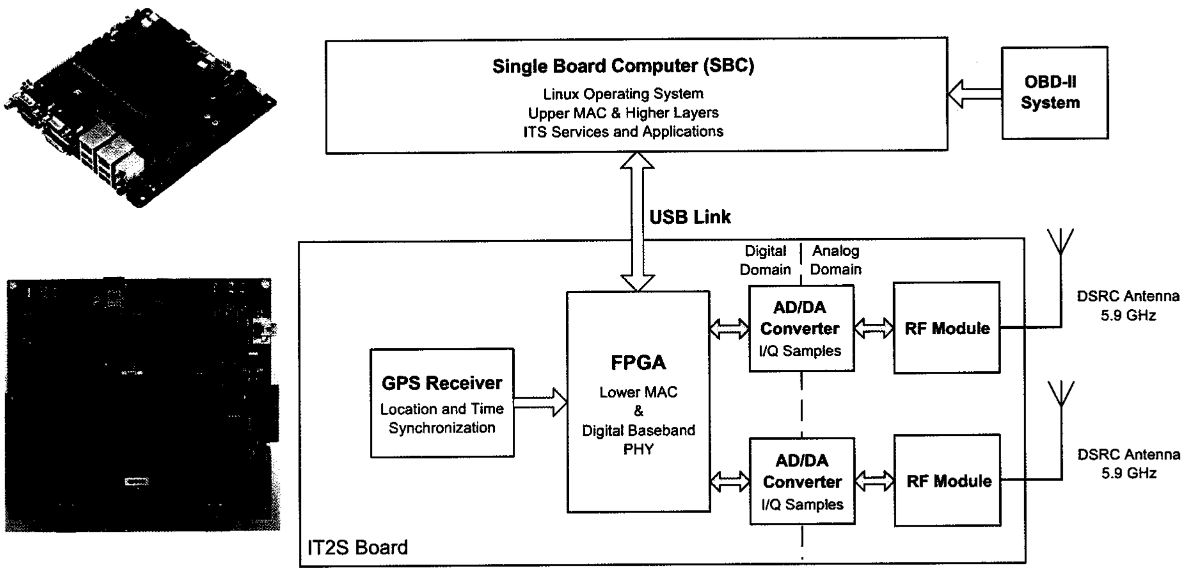

Fig. 2. IT2S platform architecture.

harmful interferences, particularly in the cases related to the blocking transmission effect. Nevertheless the impact on the PER can still be very severe under certain circumstances. Some preliminary field test results proved the large number of packet errors when an interferer working in an adjacent channel is close to the receiver node [13]. The distance for which the ACI effect starts to be critical (a PER higher than 10%) was measured and occurs whenever the interferer is closer than the intended transmitter to the receiver by an order of magnitude or more. Similar results were obtained in experimental simulations [14,15] and other field trial tests [16,17], confirming that the effect of cross channel interference cannot be neglected, specially under heavy traffic load conditions.

This issue is partially addressed in [18] by a token ring MAC protocol named MCTRP, aiming to improve throughput over all WAVE channels. The adaptive algorithm establishes virtual rings where groups of vehicles are organized, each one communicating in a specific service channel. By switching to a different SCH when the interference level increases, the protocol is able to reduce the ACI of a virtual ring. In [14], a preliminary solution to mitigate cross channel interference is proposed (Cross Channel CSMA/CA or 3CSMA/CA protocol), by reducing transmission power on the adjacent channel and by delaying potential transmissions until the reception on the adjacent channel is completed. The last measure is only taken depending if a potential receiver node is within a defined distance range or not. In order to protect safety messages exchanged on the control channel, Campolo and Molinaro [19] suggest the use of adjacent channels solely for vehicles temporarily stopped at sufficient distance from the road, such as in a gas station for refuelling. This way, it is possible to prevent a performance degradation in the CCH and at the same time, not completely waste the spectrum resources in the adjacent channels. To further reduce the effects of cross channel interference, disjoint contention window durations and Arbitrary Inter-Frame Spacing (AIFS) values [20] may be used by nearby channels to avoid collisions, as suggested in [11]. All in all, further efforts are required in the design of more efficient techniques to face ACI, since this is serious problem for the simultaneous multi-channel operation in scenarios where nodes are in close proximity.

ACI is also a concern for future 5G mobile networks, since dynamic spectrum access will likely be employed to exploit spectrum holes in existing cellular networks. Therefore, new waveforms with high spectral efficiency and low Adjacent Channel Leakage Radio (ACLR) will be required in order to cause minimum impact in legacy systems, such as current 4G networks. Several experimental studies [21,22] are being conducted with the main goal of analyzing the possible coexistence of 5G and current LTE systems. Candidate waveforms such as Generalized Frequency Division Multiplexing (GFDM) that present lower ACLR and Peak-to-Average Power Ratio (PAPR) than traditional OFDM systems, are being tested and evaluated under these scenarios.

3. Effects of ACI in the received signal

This work addresses the problem of cross channel interference on the receiver nodes of a vehicular network, through the design of a digital two-stage FIR filter. The role of this filter is to attenuate the interfering signal on the adjacent channels as much as possible, while preserving the signal received in the desired frequency. As a first step in this design process, an experimental setup was devised to capture the raw samples at the receiver platform, when both the interferer node and the intended transmitter were sending messages. This way, an analysis can be performed on the characteristics of the received signal when ACI is present and thus, the filter design process can be optimized to strongly reject the spectral components of the unwanted signal.

3.1. Experimental setup

The setup used to fully characterize the ACI effect in the received digital baseband signal, took advantage of a research platform compliant with the IEEE 802.11p protocol [23]. The architecture of this flexible vehicular communication station, named IT2S platform, is presented in Fig. 2. There are two main components: a Single Board Computer where the higher layers of the protocol stack are implemented; and the IT2S Board, responsible for the MAC and physical layer's functionalities of IEEE 802.11p standard. In this experiment, the focus was on the analog to digital interface of the IT2S board, where the raw digital in-phase/quadrature (I/Q) samples were captured for analysis. The RF module down-converts the wireless signal to baseband, where it occupies half of the RF bandwidth, i.e. 5 MHz instead of 10 MHz, and then the AD/DA Converter, working at a sampling frequency of 40 MHz,

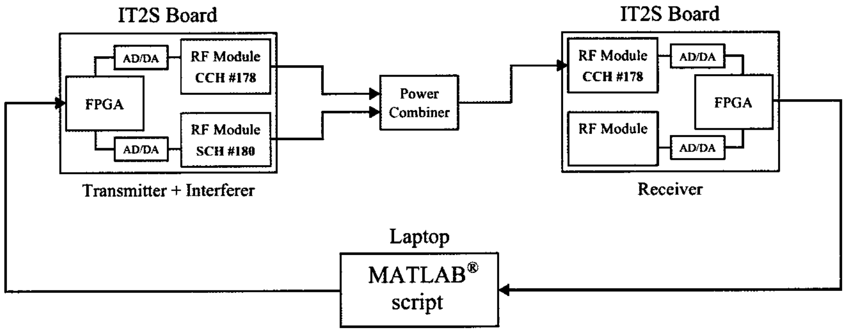

Fig. 3. Experimental setup used to analyze the effects of ACI in the received signal.

digitizes the signal before sending it to the FPGA.

The experiment was conducted in the scenario depicted in Fig. 3. Two IT2S platforms were employed, and since these are dual-radio devices as required by the ETSI ITS-G5 standards [4], a total of four radio units were available. Hence, one of the platforms was used as a transmitter and as an interferer simultaneously, with one radio tuned in the American control channel (CCH #178) and the other interfering in a adjacent service channel (SCH #180). The remaining IT2S platform was working as a receiver node with the radio where the digital I/Q samples were captured, operating in the CCH #178. All measurements were taken in a well-controlled environment, with all platforms directly connected through coaxial cables. A power combiner was used to couple the transmitted signal with the interfering one into the receiving radio. This way, the attenuation between the transmitter and the receiver was always constant and equal to the attenuation between the interferer and the receiver. The packet transmission in both radios was internally synchronized by the FPGA, forcing interference to actually happen. In the receiver node, the digital baseband samples coming from the AD/DA Converter were first stored and then retrieved from the FPGA directly to a computer, in order to be processed by a MATLAB® script. The Automatic Gain Control (AGC) mechanism was disabled in the receiving platform and a fixed gain value was used instead, in order to ensure that measurements were always taken under the same conditions.

3.2. Baseband ACI effect

Firstly, only the radio tuned in the control channel #178 was transmitting, which allows the analysis of the received signal without interference. This way and after processing the digital raw I/Q samples recorded at the FPGA input, one can obtain a Power Spectral Density (PSD) estimate of the signal captured at the receiver node. Fig. 4 shows the baseband frequency domain representation of the signal transmitted on channel #178 with approximately 7.5 dBm of power. The graphics depicts the PSD estimate from 0 to 40 MHz – the ADC's sampling frequency. As it can be observed, the bandwidth of the signal is in fact 5 MHz, half of the 10 MHz occupied in the 5.9 GHz frequency band.

By keeping the same radio sending messages and adding the other one transmitting on SCH #180, one can observe the effect of ACI in the receiver node. This result is presented in Fig. 5, where it is visible the presence of the interfering baseband signal in a channel adjacent to the transmitter. The transmitting power was the same in both channels and it was equal to the one used in the experiment of Fig. 4, i.e. ≈ 7.5 dBm. It is clearly evident the difference in the spectral components from the case where there was no interferer. In baseband and from the perspective of the receiver tuned in channel #178, the interferer occupies a bandwidth of approximately 10 MHz, from 5 to 15 MHz. For these transmitting

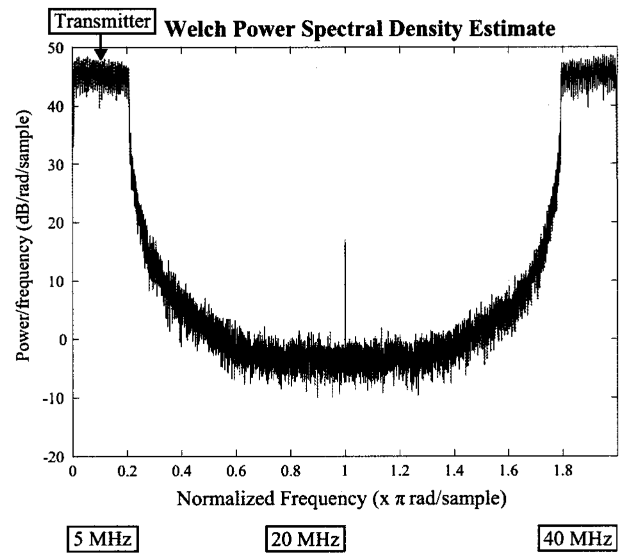

Fig. 4. Estimated power spectral density of the signal sent by the transmitter (tuned on CCH #178 and with a transmit power level of ≈ 7.5 dBm) at a sampling frequency of 40 MHz.

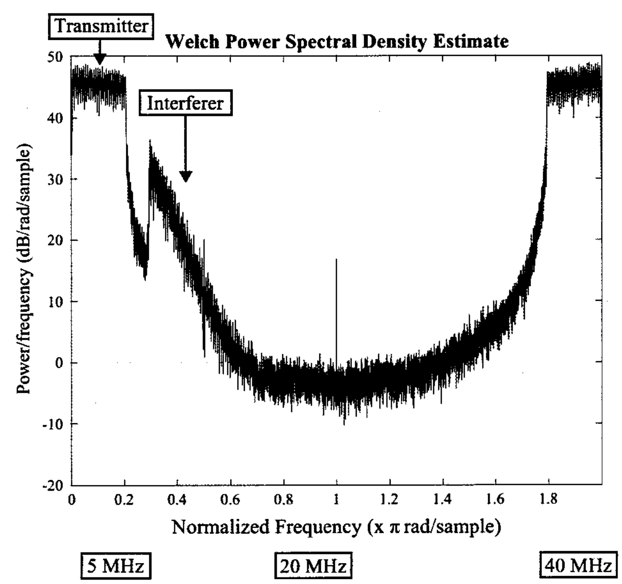

Fig. 5. Estimated power spectral density of the signals sent by the transmitter (CCH #178, ≈ 7.5 dBm) and the interferer (SCH #180, ≈ 7.5 dBm) at a sampling frequency of 40 MHz.

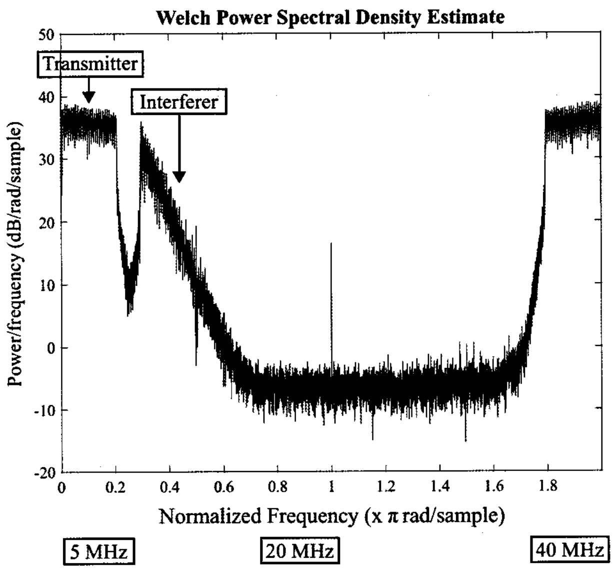

Fig. 6. Estimated power spectral density of the signals sent by the transmitter (CCH #178, ≈ -3 dBm) and the interferer (SCH #180, ≈ 27 dBm) at a sampling frequency of 40 MHz.

power levels, the peak of the unwanted signal in the frequency domain is approximately 15 dB below the signal received on the desired channel.

For the worst case scenario, i.e. when the transmitter is sending messages with the lowest power level available and the interferer is transmitting at full power, the PSD shown in Fig. 6 is obtained. In this situation, the peak of the interfering signal has almost the same value of the signal in the band of interest, being only 2 or 3 dB below. In conclusion, if no filtering operation is applied to the digital I/Q samples, the decoding process of the messages received in the scenarios presented in Figs. 5 and 6, will be seriously compromised. This problem derives from the fact that the unwanted signals in the nearby channels are not completely eliminated by the RF modules in the analog domain. In the IT2S platform, the RF module applies a low-pass filter with a cut-off frequency of 7.5 MHz, after down-converting the signal. Notice that in baseband the desired channel has a bandwidth of approximately 5 MHz and the immediate adjacent channel goes from ≈ 5 MHz to ≈ 15 MHz, thus the referred value of cut-off frequency is clearly insufficient. Under these circumstances, a more stringent filtering operation should be performed in the digital domain, using a lower cut-off frequency and a shorter transition band.

4. Digital interpolated FIR filter

Based on the previous results, it can be concluded that an interfering signal in an adjacent channel could severely affect the proper reception of messages sent by a transmitter node tuned in the channel of interest. The level of the signal generated by the interferer that appears at the FPGA input could be approximately equal to (Fig. 6) or even greater than the desired signal (a situation that would occur if an attenuator was added between the transmitter and the power combiner in the setup above, making the path loss of the interferer lower than the one of the transmitter). This interference has to be filtered in order to increase the probability of correctly decoding the received messages and to avoid the false blocking transmission effect described in Section 2. In this paper, the design and evaluation of a two-stage FIR low-pass filter are presented, with the main goal of reducing the interference due to the adjacent channels. The first stage is constituted by an

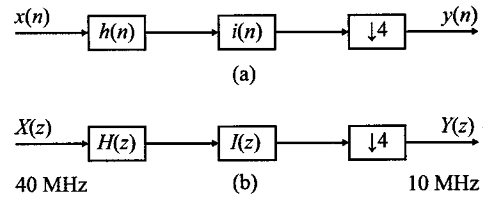

Fig. 7. Block diagram of the two-stage low-pass filter, both in (a) time and (b) frequency domains.

interpolated FIR filter, which is more efficient than a simple FIR filter, since it can achieve steeper slopes with the same filter order. However, it needs another low-pass filter to eliminate the undesired passbands resulting from interpolation. The design of this second low-pass filter is not so stringent, i.e. requires a lower filter order, and it could be implemented with a polyphase decomposed architecture, consuming few FPGA resources and taking advantage of the decimation factor of 4 that could be applied to the I/Q samples. This decimation can take place since there was an oversampling factor of 4 in the AD/DA Converter. In other words, the signal with a bandwidth of 5 MHz was sampled at 40 MHz, four times more than the required by the Nyquist theorem.

The block diagram, both in time and frequency domains, of the two-stage low-pass filter is presented in Fig. 7. The signal $x(n)$ or $X(z)$ represents the digital raw I/Q samples at the FPGA input. Then, $h(n)$ or $H(z)$ corresponds to the first stage of the filtering process – the Interpolated FIR (IFIR) filter, responsible for implementing the narrow transition band immediately after the spectrum components of the signal in the desired channel. The second stage is constituted by the polyphase decomposed filter $i(n)$ or $I(z)$, taking advantage of the decimation factor of 4, whose goal is to eliminate the frequency replicas not attenuated by the interpolated FIR filter. Finally, $y(n)$ or $Y(z)$ represents the filtered signal that will feed the digital receiver chain at a sampling rate of 10 Msps. The detailed block diagram of this two-stage low-pass filter is depicted in Fig. 8. This scheme could be easily implemented in digital hardware (FPGA) using simple processing blocks, like adders, multipliers and registers for the time delays.

The coefficients for the design of both filters were obtained in MATLAB® with the aid of Filter Design and Analysis Tool (FDAtool). For the IFIR filter, these coefficients were first computed for an equiripple FIR filter without interpolation. However, since an interpolation factor of 3 was then applied, the specified transition band was three times larger than the desired filter. After that, the design of the final IFIR filter can be concluded, by adding two null coefficients between two consecutive coefficients previously obtained in FDAtool. These zero value coefficients are naturally omitted in the top part of Fig. 8 but are implicit in the delays of 3 units (z^{-3}). The complete specifications used in the fdatool for this filter with minimum order are presented in Table 1. A passband frequency of 4.14 MHz was specified instead of 5 MHz, since the standard imposes a small band guard value of ≈ 800 kHz in each side of vehicular channels, so the actual RF bandwidth is not exactly 10 MHz but approximately 10 – (2*0.8) MHz. For the given input parameters, a minimum filter order of $N=29$ was obtained. The frequency response of the IFIR filter is presented in Fig. 9. The additional passbands resulting from the interpolation process are easily noticed, occupying a baseband spectrum between ≈ 0.45 and 0.9π rad/sample in normalized units, which corresponds to the frequency range between ≈ 9 and 18 MHz.

Following the design phase, the IFIR filter was applied to the original signal from Fig. 6, using MATLAB® code that simulates an efficient implementation in hardware, where the multipliers corresponding to the null coefficients were eliminated, just like in Fig. 8. The PSD of the signal obtained at the output of the IFIR filter is shown in Fig. 10. One can observe the strong attenuation of

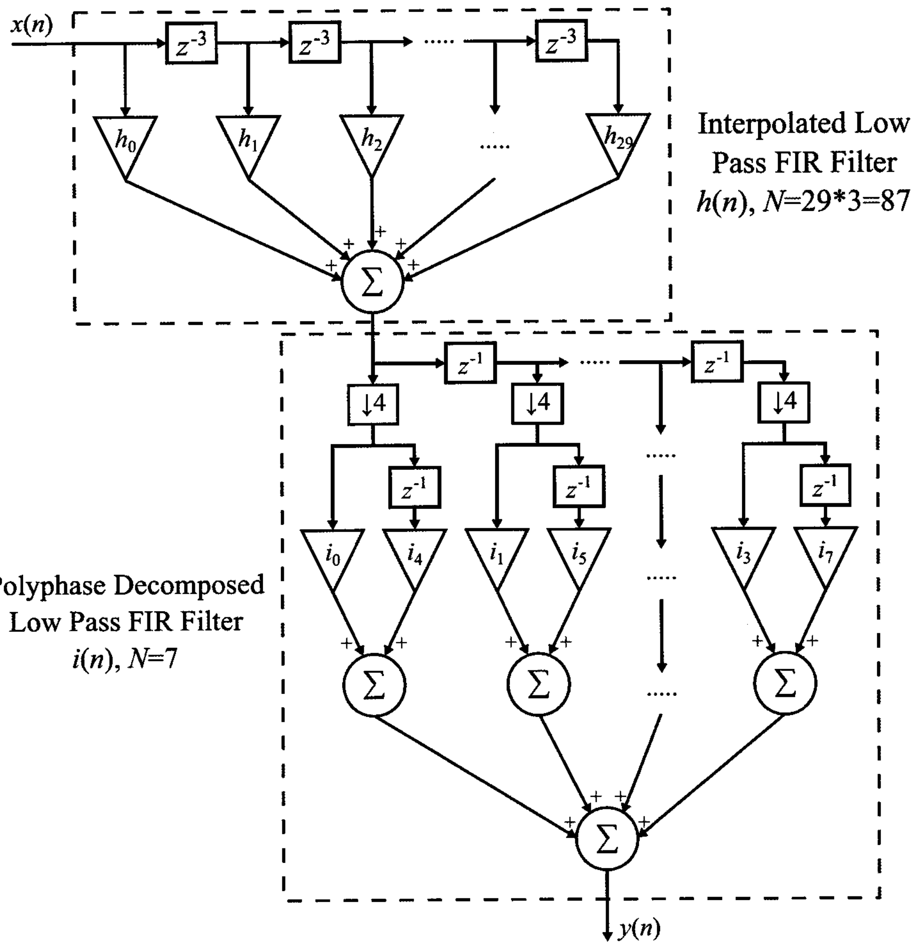

Fig. 8. Detailed block diagram of both the interpolated low-pass FIR filter (top) and the polyphase decomposed low-pass FIR filter (bottom).

Tab. 1
Interpolated FIR filter parameters in FDA tool.

Response type	Lowpass
Filter order (minimum order)	29
Design method	FIR equiripple
Sampling frequency (Fs)	40 MHz
Absolute passband	3*4.14 MHz
Frequency (Fpass)	=12.42 MHz
Normalized passband	3*0.207π rad
Frequency (wpass)	=0.621π rad
Absolute stopband	3*4.88 MHz
Frequency (Fstop)	=14.64 MHz
Normalized stopband	3*0.244π rad
Frequency (wstop)	=0.732π rad
Passband attenuation (Apass)	0.5 dB
Stopband attenuation (Astop)	40 dB

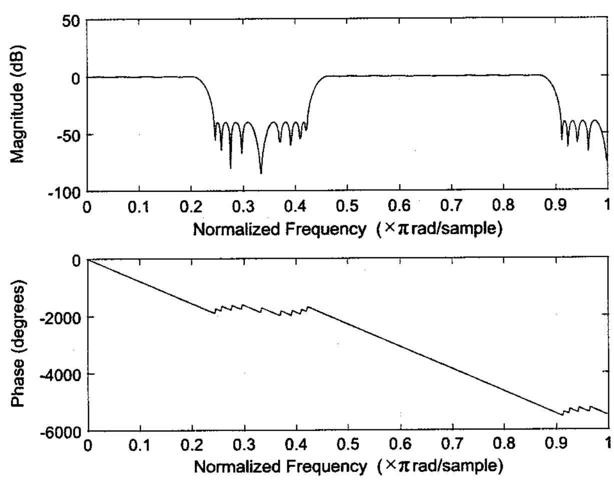

Fig. 9. Frequency response of the $H(z)$ low-pass IFIR filter.

nearly 40 dB in the peak of the original interfering signal (the gray one). However, there are replicated passbands that have to be eliminated by the second low-pass filter $I(z)$. This filter was also created in fdatool with the parameters displayed in Table 2. In this case, a filter order of $N=7$ was specified and a stopband frequency of 8.42 MHz was required in order to remove the replicas starting at ≈ 9 MHz. The frequency response of this second filter is presented in Fig. 11. As it can be seen, the transition band is more relaxed and the attenuation in the stopband is lower than the case of the IFIR filter, because a lower filter order was utilized and the frequency requirements were not so stringent. Nevertheless, these filter characteristics are sufficient to mitigate the impact of the replicated passbands in the filtered signal, represented by the black PSD in Fig. 12. The result presented in this figure is obtained before the decimation block in Fig. 6, which means that in this case the polyphase decomposition property was not applied yet. The PSD of the output signal shows that the peak value of the interferer (≈ -5 dB/rad/sample at $\approx 0.5\pi$ rad) was attenuated by 40 dB when compared to the original signal (≈ 35 dB/rad/sample at $\approx 0.3\pi$ rad). This constitutes a strong reduction in the amount

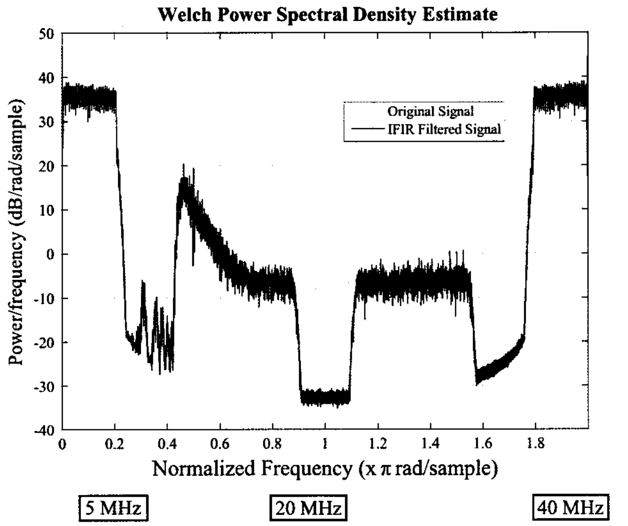

Fig. 10. Estimated power spectral density comparison between the original signal from Fig. 6 (in gray) and the signal obtained after the $H(z)$ filter (in black) at a sampling frequency of 40 MHz.

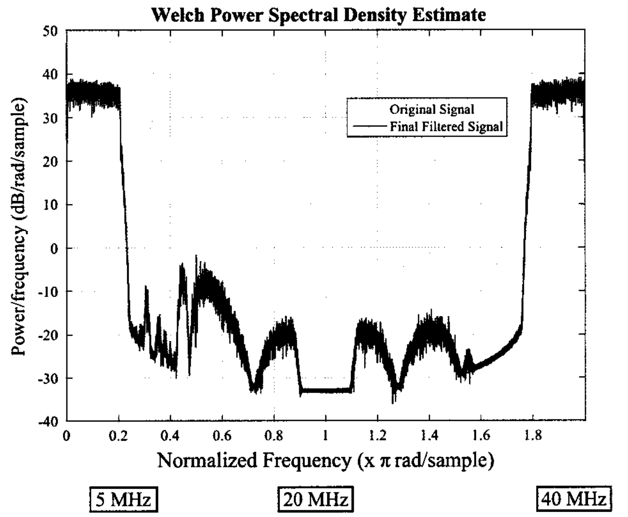

Fig. 12. Estimated power spectral density comparison between the original signal from Fig. 6 (in gray) and the signal obtained after the $I(z)$ filter (in black) at a sampling frequency of 40 MHz.

Tab. 2
Polyphase decomposed FIR filter parameters in fdatool.

Response type	Lowpass
Filter order (specify order)	7
Design method	FIR equiripple
Sampling frequency (Fs)	40 MHz
Absolute passband frequency (Fpass)	4.14 MHz
Normalized passband frequency (wpass)	0.207π rad
Absolute stopband frequency (Fstop)	8.42 MHz
Normalized stopband frequency (wstop)	0.421π rad
Passband weight value (Wpass)	10
Stopband weight value (Wstop)	1

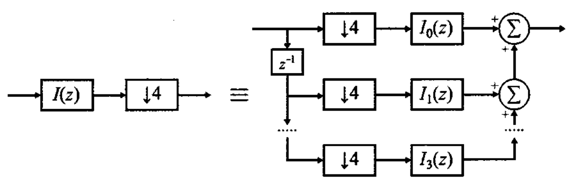

Fig. 13. Polyphase decomposed filter with a decimation factor of 4.

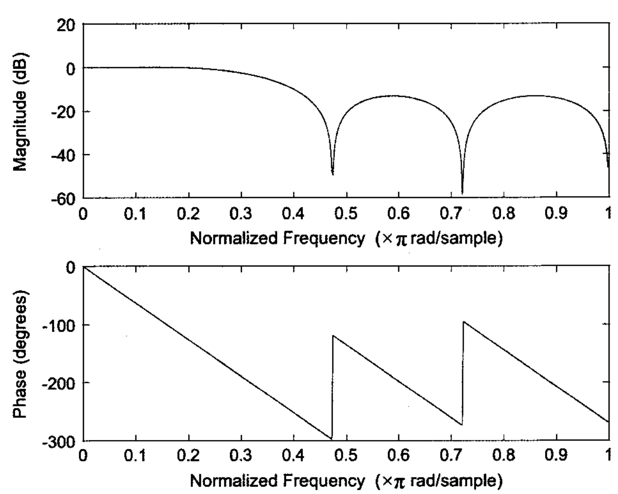

Fig. 11. Frequency response of the $I(z)$ low-pass FIR filter.

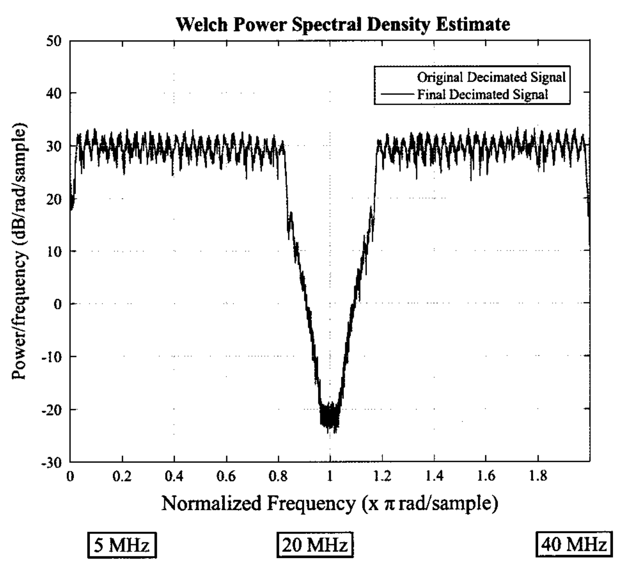

Fig. 14. Estimated power spectral density comparison between the original signal solely decimated (in gray) and the final signal obtained after the designed two-stage low-pass filter (in black) at a sampling frequency of 10 MHz.

of interference present in the received signal and increases the probability of successfully decoding the packets by the receiver node.

By taking advantage of the decimation factor of 4 (Fig. 7), the implementation of the $I(z)$ filter can be made more efficient, being the filtering operation performed at a lower data rate (10 Msps instead of 40 Msps). In this way, a polyphase decomposition with 4 phases can be employed, as depicted in Fig. 13. Thus, the polyphase decomposed $I(z)$ filter takes the shape of the block diagram presented in the bottom part of Fig. 8.

Finally, a comparison can be performed between the original situation, where the captured data was solely decimated before being processed by the digital receiver chain, and the case where the two-stage low-pass filter proposed in this paper was employed. The spectrum analysis of both resulting signals is shown in Fig. 14. The PSDs presented here correspond to the samples that would be supplied as an input to the receiver chain operating at a sampling rate of 10 Msps, thus already include the effect of the decimation by a factor of 4. As it can be observed, the transition band of the filtered signal is much sharper and an attenuation of almost 30 dB has been achieved at half of the sampling frequency.

In terms of the delay introduced in the receiver chain, its value is given by adding the delay imposed by both filters. Regarding the IFIR filter, the order of the filter built in the fdatool has to be multiplied by 3, to take into account the effect of interpolation and the zero-value coefficients added at the end. Consequently, the IFIR filter order is equal to $N=29*3=87$ and therefore, the group delay is equivalent to $((87+1)/2)=44$ clock cycles at 40 MHz, which corresponds to an absolute delay of 1.1 μs. In what concerns to the polyphase decomposed FIR filter, giving that its order is $N=7$, a group delay of $(7+1)/2=4$ clock cycles at 40 MHz is introduced, corresponding to an absolute delay of 0.1 μs. As a result, a total delay of 1.2 μs is added to the receiver chain by the cascade of the two low-pass filters. This value is perfectly acceptable for the system's operation, given the 12.8 μs available to perform frame detection and automatic gain control [2].

5. Conclusions and future work

In this paper, a two-stage low-pass FIR filter has been proposed with the main goal of mitigating the effects of adjacent channel interference in vehicular communication systems. First, an interpolated FIR filter with a narrow transition band was designed to strongly attenuate the spectral components of the interfering signal close to the desired channel. And then, a polyphase decomposed FIR filter was employed to eliminate the passband replicas of the IFIR filter. The design followed a multi-rate approach, taking advantage of the decimation block in the interface between the analog and the digital domains of the receiver chain.

The behavior of this two-stage filter was simulated and tested in MATLAB® and the results have shown that the proposed solution significantly reduces the impact of the adjacent channel transmissions in the signal of interest. Furthermore, the cascade of the two filters can be efficiently implemented in an FPGA, consuming simple digital hardware blocks. In addition, only a small delay is introduced in the decoding process of the receiving platform.

As future work, the designed filter will be implemented in an FPGA and integrated in the operation of the IT2S platform. This way, it will be possible to evaluate the performance of the proposed solution in a real-world scenario. Metrics such as packet error rates, could be analyzed under the presence of an interfering node, and the statistics could be compared with the present situation, where no filtering operation is involved.

Acknowledgments

This work is funded by National Funds through FCT - Fundação para a Ciência e a Tecnologia under the PhD scholarship Ref. SFRH/BD/52591/2014 and the project PEst-OE/EEI/LA0008/2013, by the European Union's Seventh Framework Programme (FP7) under grant agreement no. 3176711 and by BRISA, under research contract with Instituto de Telecomunicações - Aveiro.

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Appendix XXXI. Vinuth Rai et al., *Cross-Channel Interference Test Results: A report from the VSC-A project*, doc.: IEEE 802.11 11-07-2133-00-000p, (July 2007).

doc.: IEEE 802.11 11-07-2133-00-000p

Cross-Channel Interference Test Results: A report from the VSC-A project

Authors: **Date:** July 17, 2007

Name	Company	Address	Phone	email
Vinuth Rai	Toyota-ITC	Toyota InfoTechnology Center USA Technology R&D 4009 Miranda Ave. Palo Alto, CA 94304	650-251-0530	vinuth@us.toyota-itc.com
Fan Bai	General Motors	General Motors R&D Center ECI Lab 30500 Mound Road Warren, MI 48090	586-986-1457	fan.bai@gm.com
John Kenney	Toyota-TTC	Toyota Technical Center-TEMA Technical Research Department 1555 Woodridge Ave. Ann Arbor, MI 48105	574-272-1403	johnkenney@alumni.nd.edu
Ken Laberteaux	Toyota-TTC	Toyota Technical Center-TEMA Technical Research Department 1555 Woodridge Ave. Ann Arbor, MI 48105	734-995-4307	ken.laberteaux@tema.toyota .com

doc.: IEEE 802.11 11-07-2133-00-000p

Abstract

This presentation provides information about *cross-channel interference* tests performed by members of the VSC2 consortium. The tests show that a transmitter in one DSRC channel can create interference leading to *significant packet errors* in another channel. This is especially true if the interferer is an order of magnitude or more closer than the desired transmitter to the receiver, and the two channels are adjacent.

The principal portions of the draft 802.11p amendment implicated by these results are the Channel Rejection requirements in Section 17 and the Transmit Masks in Annex I.

Submission

doc.: IEEE 802.11 11-07-2133-00-000p

Background: VSC2

- Vehicle Safety Communications 2 (VSC2): A consortium under the auspices of the Collision Avoidance Metrics Partnership (CAMP)
- Members:
  - DaimlerChrysler
  - Ford
  - General Motors
  - Honda
  - Toyota
- Sponsors of VSC-Applications (VSC-A) Project in cooperation with the US Department of Transportation

Submission

doc.: IEEE 802.11 11-07-2133-00-000p

Background: VSC-A

- 3 year project - December 2006 to November 2009.
- Follow-on project to CAMP/DOT VSC (2002-2004) project.
- Goal: Determine if DSRC @5.9 GHz & vehicle positioning can improve upon autonomous vehicle-based safety systems and/or enable new communication-based safety applications.
- Strong emphasis on resolving current communication and vehicle positioning issues so that interoperable future deployment of DSRC+Positioning based safety systems will be enabled.

Submission

doc.: IEEE 802.11 11-07-2133-00-000p

VSC-A Project Organization: 10 Tasks

- Task 2:

Coordination With Standards Development Activities

  - "Continued active participation by the VSC2 consortium in the IEEE 802.11p DSRC lower layer standards development ... will be necessary"
  - "Appropriate VSC-A outcomes will be formulated as contributions to the standards groups and the active participants in these groups from the VSC2 ... will introduce and promote these contributions at the various standards meetings"

- **Subtask 5.2.5:**

DSRC WAVE Standards Validation for Safety Applications

main objectives are:

  - "validate current WAVE standards proposal with real-world vehicle environment"
  - "make recommendations to WAVE standardization group"

Quotes taken from "VSC-A Technical Proposal, November 20, 2006"

Submission

doc.: IEEE 802.11 11-07-2133-00-000p

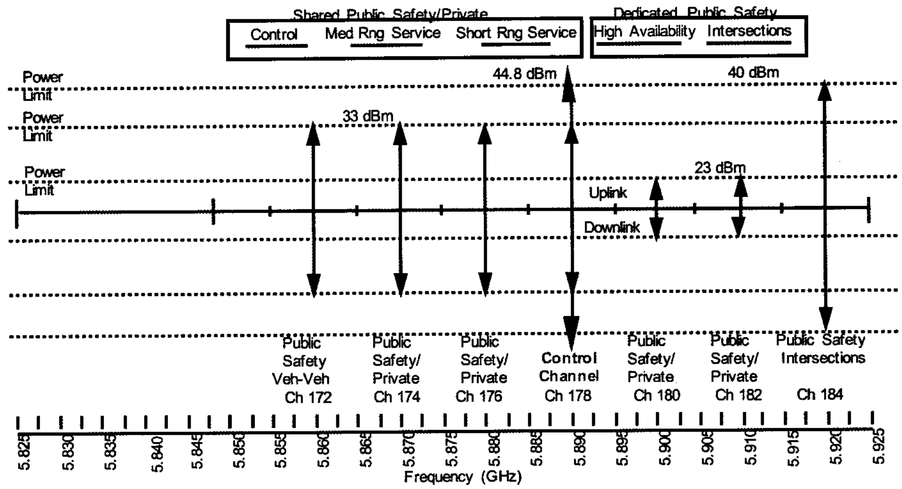
Scope of this presentation: Interference

- **Standards coordination is concerned with PHY layer, MAC layer, and higher layers**
- **PHY layer alone presents many technical challenges, including Delay spread, Doppler spread, channel models**
- **This talk is focused on *cross-channel interference*, i.e. the interference effect that a transmission in one channel has on communications in another channel**

Submission

doc.: IEEE 802.11 11-07-2133-00-000p

5.9 GHz DSRC US Bandplan (10 MHz Channels)



doc.: IEEE 802.11 11-07-2133-00-000p

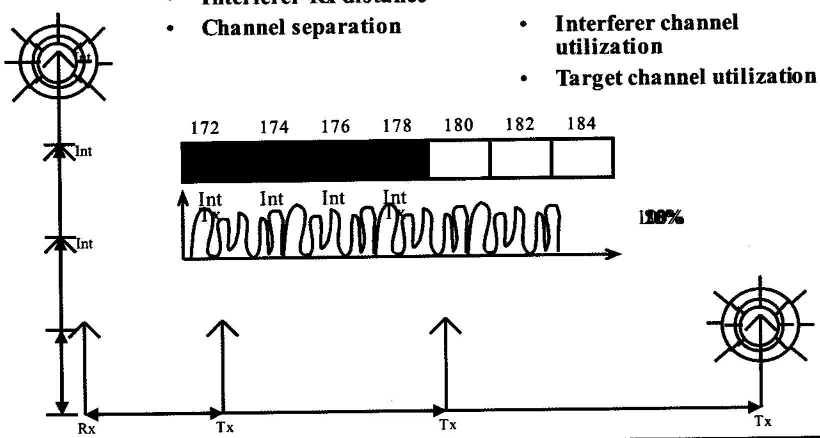
Result Preview

- **Tests indicate that an interfering transmitter can *significantly disrupt* the ability of two stations to communicate in another channel**
- **Interference effect is heightened when [transmitter-receiver] distance is ten or more times the [interferer-receiver] distance – corresponding to *antennas on adjacent vehicles or on the same vehicle***
- **Interference effect is heightened when interference channel is *adjacent to target communication channel***

Submission

Important Test Parameters

- Tx-Rx distance
- Interferer-Rx distance
- Channel separation
- Tx power
- Interference power
- Interferer channel utilization
- Target channel utilization

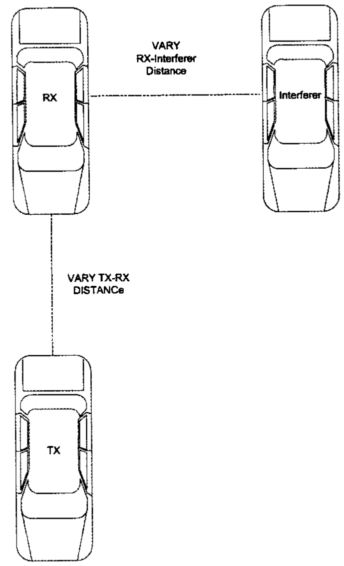


Test Sets

- **The following three organizations performed cross-channel interference tests reported here:**
  - Toyota ITC
  - General Motors
  - Toyota TTC & UC Berkeley
- **Results were reviewed by entire VSC-A team**
- **The organizations agreed on high level objectives, but determined the test details separately, to facilitate a multi-faceted view of the issue**

Test Set #1: ITC

- Ch 172 is "desired". Interferer on Ch 174, 176, 178
- Antennae mounted on stationary vehicles
- Rx-Int distances: 0.5 m to 60 m
- Tx-Rx distances: 10 to 300 m
- Interferer power: 20 dBm
- TX power: 20, 15, 10 dBm
- Interferer sending limited only by MAC gaps, ~90% active.
- New generation chipset



ITC Test Results: 0.50 m Rx-Int distance (same vehicle)

TxRx Dist	Int CH	Rx PER
25m	174	100%
50m	174	100%
100m	174	100%
25m	176	0.30%
50m	176	0.05%
100m	176	95%
25m	178	0%
50m	178	0%
100m	178	0.40%

Tx channel = 172

doc.: IEEE 802.11 11-07-2133-00-000p

ITC Test Results: PER for off-vehicle Ch 174 interferer

RX-Interferer Distance (meters)	15	25	50	100	150	200
60						0%
40					0%	10%
30				0%	1%	80%
25				0.5%	80%	99%
20				40%	90%	100%
15	0%	1%	40%	92%	95%	100%
12.5	0.10%	1.50%	70%	98%	100%	100%
10	0.90%	35%	99%	100%	100%	100%
7.5	15%	95%	100%	100%	100%	100%
5	55%	98%	100%	100%	100%	100%
2.5	95%	100%	100%	100%	100%	100%

Legend: PER > 10%

RX-TX Distance (meters)

Tx channel = 172

doc.: IEEE 802.11 11-07-2133-00-000p

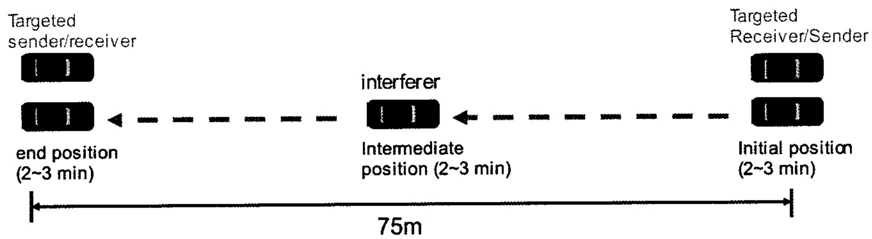
ITC Test results: non-adjacent interferer 2.5 m distance, power asymmetry

TxRx Dist	Int CH	Tx Power	Int Power	RxInt Dist	Rx PER
25m	176	20dBm	20dBm	2.5m	0%
25m	176	15dBm	20dBm	2.5m	0%
25m	176	10dBm	20dBm	2.5m	0%
50m	176	20dBm	20dBm	2.5m	0%
50m	176	15dBm	20dBm	2.5m	0%
100m	176	20dBm	20dBm	2.5m	0%
100m	**176**	**15dBm**	**20dBm**	**2.5m**	**20%**
100m	**176**	**10dBm**	**20dBm**	**2.5m**	**100%**
100m	178	20dBm	20dBm	2.5m	0%
100m	**178**	**15dBm**	**20dBm**	**2.5m**	**22%**
200m	176	20dBm	20dBm	2.5m	0%
200m	176	15dBm	20dBm	2.5m	0%
200m	**176**	**10dBm**	**20dBm**	**2.5m**	**100%**
200m	178	20dBm	20dBm	2.5m	0%
200m	178	15dBm	20dBm	2.5m	0%
200m	**178**	**10dBm**	**20dBm**	**2.5m**	**100%**

Tx channel = 172

doc.: IEEE 802.11 11-07-2133-00-000p

Test Set #2: GM



- Ch 178 is "desired". Interferer on Ch 176 or 172.
- Tx power = Interferer power = 20 dBm
- Blue and Green are both Tx and Rx, potential for collisions
- Tx-Rx distance = 75 m
- Rx-Int distance varies from ~2 m to 75 m
- Interferer load varies from 2% to 40% of channel
- Previous generation chipset

doc.: IEEE 802.11 11-07-2133-00-000p

GM Test Results

Interferer Channel	Interferer load	PER range*
none	n/a	2.6%-7.5%
172	20%	2.7%-9.1%
172	40%	2.9%-11.5%
176 (adjacent)	20%	14.4%-15.7%
176	40%	21.5%-27.1%

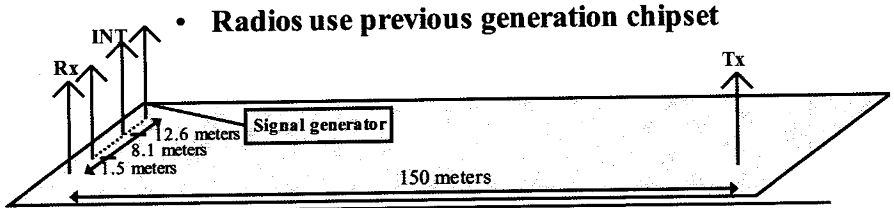
*The PER results also depend on the target channel load. E.g., the lower-bound values are achieved when target channel load is 2%, while the higher-bound values are achieved when the target channel load is 10%

Tx channel = 178

doc.: IEEE 802.11 11-07-2133-00-000p

Test Set #3: Berkeley/TTC

- Ch 172 is "desired". Interferer = 174, 176, or 178
- Antennae mounted on 6 foot poles, stationary
- Tx-Rx distance = 150 m. Int-Rx distance variable
- Tx and Interferer at 20 dBm
- Interferer signal is OFDM-like, from signal generator, active 100% of time, Class C compliant.
- Test uses "ping," so requires response.
- Radios use previous generation chipset



Submission

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Berkeley/TTC Test Results

Int. Ch.	Int-Rx	PER
178	1.5 m	0%
176	1.5 m	5%
174	1.5 m	100%
174	8.1 m	100%
174	12.6 m	0%

In this test a "packet error" is a Ping Time-Out

Tx channel = 172

Submission

doc.: IEEE 802.11 11-07-2133-00-000p

Cross-Channel Interference Data Summary

- Adjacent channel interference can create substantial packet errors when

  [Tx-Rx distance] : [Int-Rx distance]

  ratio is on the order of *10 or more* (assuming equal Tx and Int power)
- Non-adjacent channel interference is much less of an issue, but still measurable in some environments
- No significant dependence on chipset generation

Submission

doc.: IEEE 802.11 11-07-2133-00-000p

Consequences for VSC-A

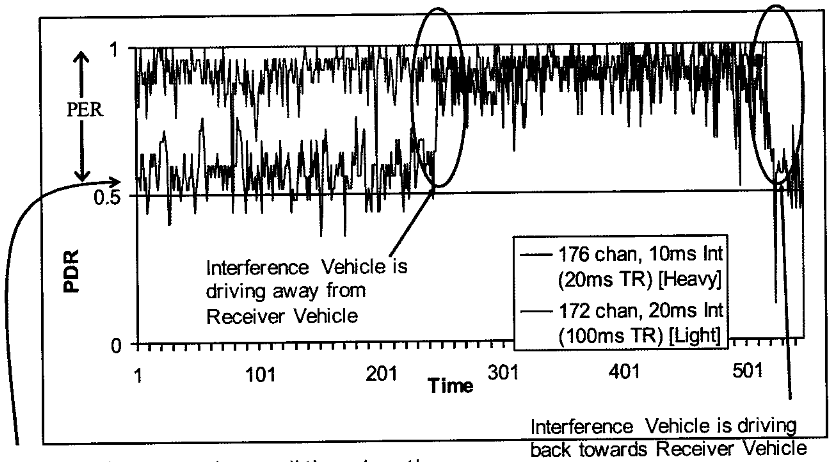
- Cross-Channel Interference calls into question the ability to use near channels within moderate proximity simultaneously
- Operating conditions that were *thought* to be acceptable apparently are not.
- Concern is heightened for applications requiring dependable communication – e.g. Safety Applications
- Specifically casts doubt on "two-independent-radio vehicle" model
- Cannot consistently provide "keep-out-range" advocated in *11-04-0143-00-wave-wave-adjacent-channel-rejection* for avoiding interference with adjacent vehicles or nearby RSE

- Conclusion: this is a serious issue for deployment models employing adjacent channels

Submission

Backup Slide doc.: IEEE 802.11 11-07-2133-00-000p

Case2: Medium-loaded Experiment Results



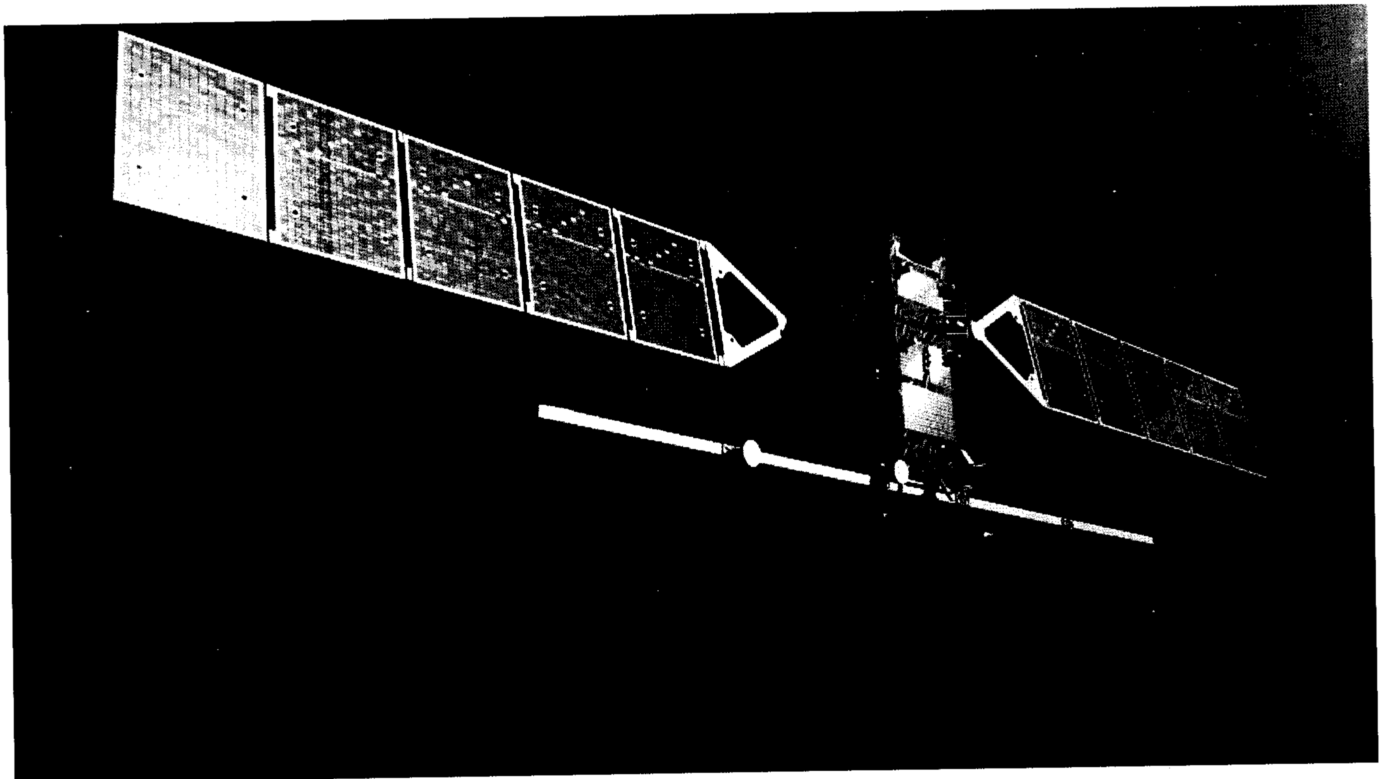
PER is 27% averaged over all three locations;

PER > 40% when close to receiver.

Submission

Appendix XXXII. Peter B. de Selding, *Europe Mounts Defense of Radar Satellite Spectrum Against Wireless Broadband Incursion*, SPACE NEWS (Jan. 24, 2014).

Europe Mounts Defense of Radar Satellite Spectrum Against Wireless Broadband Incursion - SpaceNews.com



Like the Sentinel-1 satellites (above), Canada's next-generation Radarsat Constellation Mission, including three satellites, operates in the same C-band spectrum coveted by the wireless-broadband companies — 5350-5470 megahertz. Credit: ESA artist concept

PARIS — European governments are seeking assistance worldwide in blocking an attempt by terrestrial-wireless broadband interests to use a slice of radio spectrum now reserved for radar Earth observation satellites, particularly those in development in Europe and Canada.

In a new version of a similar dispute with satellite telecommunications services operating in a different portion of the C-band spectrum, the terrestrial-broadband promoters — Cisco Systems, Intel, Qualcomm and Broadcom among them — say the frequencies in question can be shared with little or no harm to radar satellites' effectiveness.

In a mid-January submission to the 48-nation European Conference of Postal and Telecommunications Administrations (CEPT), the broadband companies say even studies that show radar Earth observation signals at their most fragile end up concluding that Wi-Fi use and radar satellite imagery can coexist without interference.

"Sharing between [C-band radar satellites] and [Wi-Fi] is feasible," the terrestrial broadband group said, referring to RLANs, or radio local area networks including Wi-Fi. The study assumed that 95 percent of Wi-Fi use occurred indoors, limiting signal propagation outside that would confront the satellite signals. That is not the view of France, Britain and the 28-nation European Commission, which are now preparing to launch three Sentinel-1 spacecraft, the first set to enter operations by this summer. The Sentinel-1 satellites are part of the Copernicus environment-monitoring network being built by the European Commission.

The EC and the 20-nation European Space Agency together have invested 3.4 billion euros ($4.6 billion) in Copernicus, with another 3.8 billion euros planned by the EC between 2014 and 2020.

"SAR measurements would be heavily interfered with if the RLANs are allowed to operate in this frequency band," ESA said in a presentation to CEPT, referring to the radar satellites' synthetic aperture radars. "This would mean severe disruption of the SAR measurements over all populated areas: urban, suburban and even rural."

Like the Sentinel-1 satellites, Canada's next-generation Radarsat Constellation Mission, including three satellites, operates in the same C-band spectrum coveted by the wireless-broadband companies — 5350-5470 megahertz.

The CEPT attempts to force common positions in advance of the World Radiocommunication Conference, held every three or four years to assign wireless frequency rights and satellite orbital slots. Organized by the International Telecommunication Union, a United Nations affiliate, the next conference is scheduled for 2015.

CEPT and its counterparts in the Americas, Africa and Asia are now sorting through the issues expected at the conference and determining what position to take there.

With the explosion of demand for mobile broadband — some 30 billion Internet-connected mobile devices are expected to be in service by 2020 — network operators and equipment providers are desperate to find additional radio spectrum in which to operate.

The demand for spectrum is one reason certain mobile satellite service providers in the United States have been subject to so much market speculation and bidding wars, even after some have failed in their core mission: They have rights to radio spectrum that could be used for mobile broadband.

Earth observation service providers are generally viewed — by their own assessment — as even less adept at political lobbying than satellite telecommunications operators, who only late in the game coalesced into a single team to preserve their use of C-band during the 2007 World Radiocommunication Conference. Even this victory was only partial. Satellite telecommunications officials expect a repeat battle in the 2015 conference over the 3-gigahertz section of C-band.

France, Britain, the European Commission and the World Meteorological Organization nonetheless have begun raising the issue to prepare for the conference.

At a Jan. 17 summit in Geneva of the 89-nation Group on Earth Observations, the French, British and World Meteorological Organization delegations said the loss of Sentinel-1 data would affect all nations. The Australian and ESA delegations to the meeting asked the group's secretariat to "develop resources" to enable nations to lobby International Telecommunication Union members in advance of the 2015 conference.

The radar satellite system backers say they deliberately selected the 5350-5470-megahertz range following the 2003 World Radiocommunication Conference decision to allocate other portions of the band to terrestrial wireless applications.

"ESA decided to operate the Sentinel-1 SAR in this 'safe' band, where no mobile systems are present," ESA said in its presentation to CEPT. "Other space agencies — Canada, China — took similar decisions."

One ESA official said China's delegation to the Jan. 17 summit in Geneva declined to endorse the French and British position, saying China's upcoming radar satellites will not be operating in the affected spectrum.

Whether China will endorse the position of France, Britain, the World Meteorological Organization and ESA at the 2015 conference is unclear. Most governments have yet to arrive at firm conclusions about the multiple issues expected during the four-week conference.

The U.S. government has been seen as generally backing the terrestrial broadband providers given the overwhelming demand for broadband.

Despite the European Commission position, even the CEPT remains uncertain of how to proceed. In a Jan. 17 statement following its meeting in Rome, CEPT said the disposition of the C-band spectrum is "subject to further consideration taking into account sharing and compatibility studies." There is "no common view" among CEPT members, its statement said.

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Appendix XXXIII. Federal Highway Administration, *Detection Technology for IVHS* (1996).

Detection Technology for IVHS, N/A

1. Scope of the Study

1.1 INTRODUCTION

Maximizing the efficiency and capacity of the existing ground transportation network is made necessary by the continued increase in traffic volume and the limited construction of new highway facilities in urban, intercity, and rural areas. Smart street systems that contain traffic monitoring detectors, real-time adaptive signal control systems, and motorist communications media are being combined with freeway and highway surveillance and control systems to create smart corridors that increase the effectiveness of the transportation network. The infrastructure improvements and new technologies are, in turn, being integrated with communications and displays in smart cars to form Intelligent Vehicle-Highway Systems (IVHS). Since the inception of this contract, Intelligent Transportation Systems (ITS) has replaced IVHS to represent the marriage of smart vehicles with smart infrastructure systems. As IVHS is included in the contract title, it is retained in this report.

Vehicle detectors are an integral part of nearly every modern traffic control system. Moreover, detectors and communications media will be major elements in future traffic monitoring systems. The types of traffic flow data, their reliability, consistency, accuracy, and precision and detector response time are some of the critical parameters to be evaluated when choosing a vehicle detector. These attributes become even more important as the number of detectors proliferate and the real-time control aspects of IVHS put a premium on both the quantity and quality of traffic flow data used in traffic surveillance and control algorithms.

Current vehicle detection is based predominantly on inductive loop detectors installed in the roadway subsurface. When properly installed and maintained, they can provide real-time data and a historical database against which to compare and evaluate more advanced detector systems. Alternative detector technologies being developed provide direct measurement of a wider variety of traffic parameters, such as density, travel time, and vehicle turning movement. These advanced detectors provide more accurate data; parameters that are not directly measured with previous instruments; inputs to area-wide surveillance and control of signalized intersections and freeways; and support of motorist information services. Furthermore, many of the advanced detector systems can be installed and maintained without disrupting traffic flow. The less obtrusive buried detectors will continue to find applications in the future, as for example, where aesthetic concerns are dominant or procedures are in place to monitor and repair malfunctioning units on a daily basis.

1.2 PROJECT OBJECTIVES

The objectives of the Federal Highway Administration (FHWA)-sponsored *Detection Technology for IVHS* project were to:

- Determine the traffic parameters and their corresponding accuracy specifi-cations needed for future IVHS applications;
- Perform laboratory and field tests with detectors that apply technologies compatible with above-the-road, surface, and subsurface mounting to determine the ability of state-of-the-art detectors to measure traffic parameters with acceptable accuracy, precision, and repeatability;
- Determine the need and feasibility of establishing permanent vehicle detector test facilities.

In performing the technology evaluations and in analyzing the data, focus was placed on the underlying technology upon which the detectors were based. It was not the purpose of the program to determine which specific detectors met a set of requirements, but rather whether the sensing technology they used had merit in measuring and reporting traffic data to the accuracy needed for present and future applications. Obviously, there can be many implementations of a technology, some of which may be better exploited than others at any time. Thus, a technology may show promise for future applications, but the state-of-the-art of current hardware or software may be hampering its present deployment.

The project consisted of 12 major tasks:

Task A. Develop a working paper that defines IVHS traffic parameter specifications for the following application areas:

- Interconnected Intersection Control,
- Isolated Intersection Control,
- Freeway Incident Detection,
- Traffic Data Collection,
- Real-Time Traffic Adaptive Control,
- Vehicle-Roadway Communications.

Task B. Select sites for detector field tests. Test sites in three different regions of the country will be selected to provide a range of environmental and traffic conditions broad enough to ensure the utility of the test results on a nationwide basis.

Task C. Develop vehicle detector laboratory test specifications and a laboratory test plan.

Task D. Select and obtain vehicle detectors for testing.

Task E. Conduct laboratory detector tests and generate a report describing the results.

Task F. Develop vehicle detector field test specifications and field test plan.

Task G. Install vehicle detectors at field test sites and collect detection technology evaluation data.

Task H. Generate detection technology field test results.

Task I. Determine which of the currently available vehicle detectors meet the IVHS criteria of Task A.

Task J. Determine the need and feasibility of establishing permanent vehicle detector test facilities.

Task K. Prepare a draft final report.

Task L. Prepare the final report that incorporates comments received from FHWA and others.

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2. Synopsis of the Final Report

The Task L Final Report contains a summary of the types and accuracies of traffic data that may be useful for several IVHS traffic management strategies, the planning that went into the execution of the project, and the data and conclusions from the Detection Technology for IVHS project that ran from September 1991 through April 1995. This section presents a summary of the findings from the Final Report. The complete Table of Contents from the Task L Final Report is included in Appendix A to provide more comprehensive information about the contents of the report.

2.1 ABSTRACT

As part of the U.S. FHWA-sponsored *Detection Technology for IVHS* program, ultrasonic, microwave radar, infrared laser radar, nonimaging passive infrared, video image processing with visible and infrared spectrum imagery, acoustic array, high sampling rate inductive loop, conventional inductive loop, microloop, and magnetometer detector technologies were evaluated at freeway and surface street arterial sites in Minnesota, Florida, and Arizona. These states were chosen because they exhibited a wide range of climatic conditions. The criteria for selecting the detector evaluation sites included searching for roadways with high traffic density and suitable structures for mounting the overhead detectors. Approximately 5.9 Gbytes of digital and analog vehicle detection and signature data and more than three hundred video tapes of the corresponding traffic flow were recorded. The detector outputs were time tagged and recorded on 88 Mbyte magnetic cartridges by using a data logger specifically designed and built for this project. Data analysis software was written to convert the raw data into an easily accessible Paradox database format compatible with a Windows personal computer operating system. Traffic volume ground truth data, obtained by counting vehicles from the recorded video imagery, were compared with the counts from the detector outputs. Speed ground truth data, obtained by driving probe vehicles through the field of view of the detectors and noting the vehicle speed as measured by the vehicle instrumentation, were compared with the speed measurement from the detectors. Several types of detectors were found to satisfy current traffic management functions. However, improved accuracies and new types of information may be required from detectors for future traffic management applications.

2.2 TRAFFIC PARAMETERS

Flow rate, speed, and density (or its surrogate occupancy) are interrelated and together describe the quality of traffic flow on a highway.1 To measure flow rate accurately, detectors need to discriminate between vehicles traveling with spatial gaps on the order of one to two car lengths and average time headways of about 1.5 to 2 seconds, although headways of 0.5 second are not uncommon in congested areas. Speeds have been measured in the past with speed traps composed of two closely spaced (ten to twenty feet apart) inductive loop detectors; a single detector with multizone capability that makes use of time of passage information; or with microwave radar, laser radar, or ultrasonic detectors that exploit the Doppler effect. Density (vehicles per mile per lane) is difficult to measure directly, except with some type of picture format such as video imaging or aerial photography, although indirect measurement is possible by dividing measured traffic flow (vehicles per hour per lane) by speed (miles per hour). Consequently, lane occupancy (the percent of time the detection zone of a detector is occu-pied by a vehicle) is often used as a surrogate measure for density. To accurately measure occupancy, the time that vehicles are within a detector's sensing area must often be known to within 1 to 5 percent of its true value.

Other traffic management parameters of importance include presence, queue length, travel time, intersection turning movements, and vehicle classification. Presence needs to be measured, even if the vehicle is stopped, for signal activation applications. Therefore, detectors that require motion to be activated, e.g., Doppler-type microwave detectors, magnetic detectors, and some infrared, cannot perform this task.

Queue length requires wide area detection to be measured directly, as does density. Point detectors that measure presence at specific distances from a stop line can be used to estimate queue length. Travel time is inversely proportional to average speed. However, for travel time to be measured directly, a network-wide interrogation system is needed. Thus, travel time could be a side benefit of instituting an automatic vehicle identification (AVI) system in which the vehicles act as "probes". However, AVI systems are beyond the scope of the field test portion of this project. Imaging systems, high resolution ranging systems such as laser radars and some ultrasonic systems, and inductive loop detectors (ILDs) coupled with special vehicle transmitters and receivers also have the ability to classify vehicles.

2.3 SAMPLE TRAFFIC PARAMETER SPECIFICATIONS FOR IVHS

Guidelines were developed to assist the reader in defining the traffic measurement needs and detector performance requirements for representative IVHS services. However, no claim is made as to the widespread applicability of the specifications since they will necessarily vary with the selected IVHS architecture, implementation strategies, selected components and signal processing algorithms, and system operational procedures.

The traffic parameter specifications for a given management strategy must primarily take into account the data processing and traffic control algorithms for which these parameters serve as inputs. Specification of traffic parameter accuracy, therefore, cannot be separated from the overall system level analysis and design process. For each contemplated IVHS service, there are likely to be many different system algorithms, procedures, and detection subsystem design options. Evaluating the alternative implementation for a particular service is the responsibility of system analysts and designers. This report cannot serve as a substitute for a thorough systems analysis and design effort. Nonetheless, a process is suggested for the development of traffic parameter specifications that include data types, collection interval, and accuracy.

To structure the discussion and presentation of detector performance specifications, three general categories of traffic parameters are defined based on their intended use and the required timeliness of their input for the real-time traffic management strategy. These categories are tactical, strategic and *historic*. While the same raw inputs may often feed each of the categories, each presents a somewhat different set of detection perform-ance and sampling requirements. In fact, these differences can result in a detector technology or product being adequate for some applications and not for others.

The traffic parameter input ranges and accuracies identified are for some of the more common IVHS services that include signalized intersection control, freeway incident management, and freeway metering control. The parameters are categorized as either tactical, strategic, or historic. Range and accuracy values are derived or inferred from the accuracy needed for use in a particular algorithm (when it is known) and from practical experience with operating systems. Many of the historic and strategic category parameters may also be applicable to a host of other static and dynamic trip/route planning-related IVHS services. However, for these and other services where established strategies and algorithms are less common, a system-specific parameter requirements analysis effort is suggested. Such analysis is beyond the scope of this study.

To a large extent, current traffic management systems are input constrained. That is, a complete microscopic (vehicle-by-vehicle) view of the traffic stream is not available in today's systems because of the lack of applicable real-time input data, even though the accelerating advances in computer processing and distributed system designs make possible advanced traffic optimization modeling and control in near real time. In this case, current systems rely heavily on prestored turning movement and origin-destination (O-D) data to supplement incomplete real-time data. In real-time control, the analysis and response to external events are performed and determined within specified time limits, usually of the order of seconds or milliseconds. In near real-time control, the feedback response is calculated within longer time intervals that are not small enough to respond to the stimuli in real time, but are sufficiently small to still have a positive impact on the events caused by the stimuli.

It is difficult to calculate the accuracy re-quired of traffic parameters for applications where algorithms do not exist or where improved algorithms are being sought. Future applications will not likely require a whole new set of traffic parameters. Rather, advanced detector technologies will provide greater area coverage with better vehicle characterization (e.g., presence, speed, classification, and turning movements), increased reliability, and reduced costs. Advanced control systems with vehicle tracking capabilities are also being developed and tested. These technology trends will be key enabling factors in the widespread deployment of advanced control algorithms that may include neural networks and expert system techniques. The net result will be an increased emphasis on tactical-type inputs and on requirements for increased accuracy and precision.

Figure 1 shows a formal process for development of traffic detector specifications. The first phase requires a detailed up-front systems analysis to properly specify all the subsystems that are part of the traffic management system architecture. Among these is the detection subsystem highlighted in the figure. The critical first step in defining traffic parameter specifications, such as signal processing algorithms, types of output data (count, speed, occupancy, etc.), parameter accuracies, data collection interval, and spatial resolution, is the identification of the overall system requirements, shown as inputs to the systems analysis process. These are normally based on a higher level evaluation of system goals and objectives [L.A. Klein *et al.*, 1993].[2]

2.3.1 Detector Specification Development

Figure 1 shows a formal process for development of traffic detector specifications. The first phase requires a detailed up-front systems analysis to properly specify all the subsystems that are part of the traffic management system architecture. Among these is the detection subsystem highlighted in the figure. The critical first step in defining traffic parameter specifications, such as signal processing algorithms, types of output data (count, speed, occupancy, etc.), parameter accuracies, data collection interval, and spatial resolution, is the identification of the overall system requirements, shown as inputs to the systems analysis process. These are normally based on a higher level evaluation of system goals and objectives [L.A. Klein *et al.*, 1993].[2]

To meet the requirements for a particular traffic management application, a number of subsystem architectures, algorithms, and traffic parameters can be selected to function either singularly, or in combination with one another. The alternatives must then be analyzed and their performance compared with the overall system goals and objectives. The analysis of the alternatives not only requires a knowledge of the basic system requirements, but also a detailed understanding of the system's targeted operating environment and the constraints imposed by the available technologies that are a part of the solution. Knowledge of key technical specialty areas is needed so that they may be applied effectively in the development and implementation of IVHS architectures. These specialties include traffic surveillance and control algorithm design, traffic flow theory, statistics and sampling theory, computer technology, communications technology, and detector technology.

Once the systems analysis phase is complete, the detection subsystem design phase can begin. The major components of this phase are location of the detector stations, selection of detector technologies (there may be more than one), definition of station configurations, and definition of detector specifications.

2.3.2 Traffic Parameter Categories

The definition of traffic parameter specifications for IVHS used here takes into account three categories of parameters: tactical, strategic, and historic. Each suggests different usage of the data by a traffic management application that, in turn, generally dictates a different set of parameter specifications including data collection interval, range, and accuracy.

2.3.2.1 Tactical Input Parameters

Tactical parameters are those utilized in tactical decision making. Tactical decisions are defined as the expedient decisions made by a control system in response to real-time traffic parameter inputs. Tactical decisions are typically based on rote logic embedded in a predefined algorithm. One example is the real-time adjustment of a traffic-adaptive controlled signalized intersection in response to the measured cyclic traffic flow profiles on each approach. Another example is the decision to declare a freeway "incident" condition in response to a mainline lane parameter value exceeding a prescribed threshold.

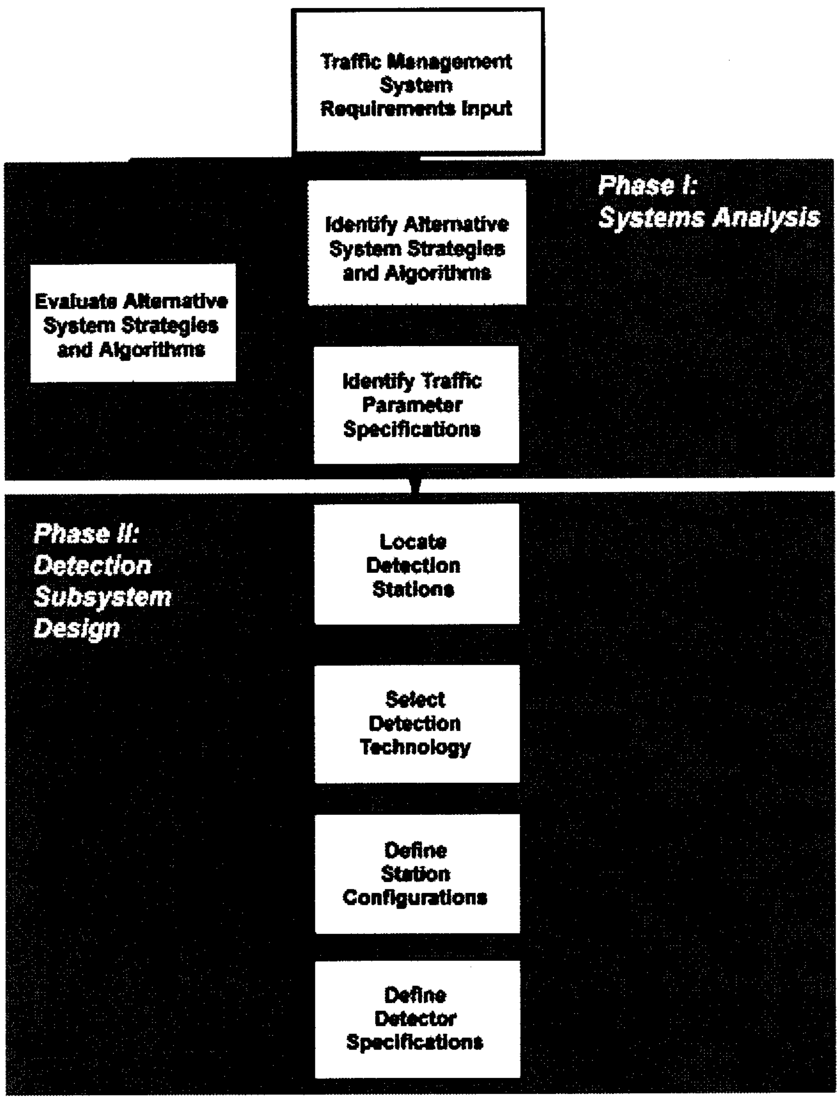


Figure 1. Detector specification process

Because tactical decisions are made in quick response to changing real-time traffic variables, tactical parameters are generally collected over short time intervals (usually of the order of a few seconds). They may also be event driven, as for example a vehicle detected by a presence detector. Since tactical parameters are collected on these shorter intervals, fewer vehicles are included in each sample. Variation from sample to sample will be exhibited due to the random nature of vehicle arrivals. The limited sample size will usually impose increased accuracy and precision on the measurement of tactical parameters. For example, the measurement of approach speed as an estimate of travel time for vehicles approaching a signalized intersection requires increased accuracy and precision when traffic signal offset decisions are being made, as compared to measuring average approach speeds for strategic background "plan-based" decision making.

2.3.2.2 Strategic Input Parameters

Strategic input parameters support strategic level decisions. These traffic control and management decisions generally operate at a higher level in the system hierarchy than do tactical decisions. Strategic decisions are typified by the activation of a preplanned management strategy in response to broad indicators of traffic flow conditions.

Strategic level decisions are often broader in geographic scope than tactical ones and often change the mode of an entire system or a large subsystem. Strategic decisions can be expert system rule-based, as in the Los Angeles Smart Corridor Management System, or algorithm-based, as used in Urban Traffic Control System (UTCS) plan selection. They frequently employ predefined scenarios and operator confirmation and approval processes.

Strategic traffic parameters are usually collected over a period of minutes rather than seconds; as a result, samples are larger. Most currently deployed freeway management and centralized traffic signal control systems use running averages and other filtering techniques to smooth out short term variations in the traffic stream data. Strategic traffic parameters are often input to maintain online data bases of current traffic conditions used by the management systems.

One example of a strategic level decision process is the selection of an incident management plan in response to a detected incident on a surface street network. When an incident condition is declared, the strategic decision process might monitor overall network conditions and implement an appropriate control plan overriding or adjusting the tactical level decision making process.

2.3.2.3 Historic Input Parameters

Historic input parameters are those used to maintain or update online historic traffic databases. These databases typically include traffic data collected over periods of five minutes or greater and are archived by time of day and day of week or by time of day and date. The primary purpose of historic data-bases is to provide information for offline planning and design operations. However, historic data are also commonly used as inputs to online tactical and strategic decision processes. For example, most freeway management systems maintain a file of historic flow rate data. This file is regularly used online as input for predicting future near-term traffic demands. In addition, some UTCS applications use historic flow rate data as input to online detector failure monitoring logic.

2.3.3 Matching Traffic Parameter Needs to Selected IVHS Services

As previously discussed, individual traffic parameters and accuracies required for a given application are specified by the algorithms, strategies, and operating procedures used to implement that application. A list of criteria which can help select traffic parameters for use in a particular IVHS application include:

- Convenience of parameter measurement;
- Amenability of resultant data to real-time processing;
- Existence of significant differences in parameter values within the range of traffic conditions that must be monitored.

Traffic parameter range, collection interval, and accuracy for application to signalized intersection control, freeway incident management, and freeway metering are presented in Tables 1 to 3. Unfortunately, the search of the available literature uncovered little universally applicable information regarding the required accuracy of traffic parameters for these or other services. Consequently the specifications presented are based on: (1) the data that were located, (2) operating experience, and (3) sensitivity analyses developed during the study or found in the literature. The estimates are considered representative of those for the selected traffic parameters and are consistent with the general requirements of the particular application. However, for those parameter specifications applicable to a specific system design or to services not covered, a detailed analysis is recommended. Such analyses are outside the scope of this study.

2.3.3.1 Signalized Intersection Control

Table 1 gives selected traffic parameter specifications for advanced signalized intersection control applications. Parameters are listed for the tactical, strategic, and historic categories. Tactical parameters include those relating to flow, speed, and occupancy measurements. For advanced signal control systems, typical flow-related parameters may include cyclically collected intersection approach flow rates, flow profile data, and turning volumes.

Tactical information related to intersection control is often collected on a cyclic basis and normalized to hourly rates. This minimizes the short term parameter fluctuations caused by data collection intervals being inconsistent with whole multiples of the cycle length. This problem can also be resolved by maintaining weighted running averages and by various other smoothing techniques [A. Gelb, 1980].[3]

Speed-based parameters are also of benefit to advanced signal control algorithms. In a tactical sense, vehicle approach speeds can be used to estimate link travel time. However, the accuracy of the speed measurement is critical in this case because a small error can have a significant effect on calculated travel time. (This depends, of course, on the length of the approach section.) An error in calculated travel time of only a few seconds can have an adverse effect on operations if travel time is used as the basis for offset calculations. Another useful speed measure is the distribution of approaching vehicle speeds. The standard deviation of the measured speed can serve as an important input to the modeling of platoon dispersion from one signalized intersection to another.

Occupancy-based measures such as queue length, delay, and percent of stops collected on a cycle basis can also be tactical inputs to advanced signal control algorithms. Data from traditional inductive loop traffic detectors on an approach to a signalized intersection provide estimates for these parameters using an input-output model which also receives the current green state of the traffic signal. These parameters provide feedback on the effectiveness of the current traffic control operation. Stop bar demand presence and queue overflow presence are two other occupancy-related parameters used by some signal control algorithms.

The strategic level parameters most often used by intersection control logic include smoothed volume, occupancy, and average speed indicators. Some systems also tabulate parameters such as average approach delay and percent of vehicles stopping or total stops by approach. Strategic data are normally kept as smoothed values (weighted running averages) with collection intervals ranging from one to five minutes. In most instances, the purpose of strategic volume data collection is to tabulate current demands for network links. Similarly, occupancy parameters are often used to monitor the extent of current congestion on the roadway network. As discussed in a previous example, strategic traffic parameters can be useful for implementing incident management strategies designed for surface street applications.

Table 1. Signalized intersection control traffic parameter specifications Tactical parameters

Parameter	Units	Range	Collection Interval	Allowable Error
Approach Flow Profiles	vehicles	0-3	1 second	± 2 veh/signal cycle
Turning Movement Vol	vehicles	0-200	1 cycle	± 2 veh/signal cycle
Average Link Travel Time	seconds	0-240	1 cycle	± 2 seconds
Average Approach Speed	mph	0-100	1 cycle	± 2 mph(0-55 mph)
Queue Length	vehicles/lane	0-100	1 second	± 2 vehicles
Demand Presence	Yes/No	–	10 Hz (minimum)	No missed vehicles
AverageApproach Delay	sec/veh	0-240	1 cycle	± 2 seconds
Approach Stops	stops	0-200	1 cycle	± 5% of stops

Strategic parameters

Parameter	Units	Range	Collection Interval	Allowable Error
Flow Rate (Volume)	veh/hr/lane	0-2500	5 min	± 2.5% @ 500 veh/hr/lane
Occupancy	%/lane	0-100	5 min	± 5% occupancy
Average Speed	mph	0-100	5 min	± 2 mph(0-55 mph)
Average Delay	sec/veh	0-240	5 min	± 2.5 seconds
Percent Stops	%	0-100	5 min (approx)	± 5%

Table 1. Signalized intersection control traffic parameter specifications (continued)Historic parameters

Parameter	Units	Range	Collection Interval	Allowable Error
Turning Movement Vol	veh/movement	0-2000	15 min	± 2.5% @ 500veh/hr
Flow Rate(volume)	veh/hr/lane	0-2500	15 min	± 2.5% @ 500veh/hr
Occupancy	%	0-100	15 min	± 5% occupancy
Average Speed	mph	0-100	15 min	± 2 mph(0-55 mph)

Historic parameters used in intersection signal control applications include link-based volume, occupancy, and speed. Turning movement and O-D pattern information are also important as inputs to demand prediction algorithms. These data are currently obtained using manual techniques.

2.3.3.2 Freeway Incident Management

Table 2 identifies selected parameter specifications for freeway incident management. Tactical parameters serve as key inputs to automated incident detection algorithms. Basic tactical inputs include lane specific mainline flow rate, occupancy, and average speed. Other tactical parameters derived from these basic parameters include spatial occupancy differential and spatial average speed differential. For incident detection logic based on California-type algorithms, the spatial differential parameters provide measures of the difference in lane specific values of occupancy or speed between successive upstream and downstream detection stations for a given direction of travel. These types of algorithms rely on the identification of an incident between mainline stations from significant differences in the measured values of parameters between the two stations. Another algorithm uses the standard deviation of vehicle speed to predict when freeways are reaching capacity and to initiate strategies such as speed limit reduction or metering [R.D. Kuhne, 1991].[4]

Strategic level parameters are important as traffic monitoring inputs to the overall incident management process. Strategic level parameters include mainline lane specific flow rate, occupancy, average speeds, and freeway on-ramp and off-ramp flows. Alternative route data are also collected when applicable. As a minimum, flow rates and link speed or travel times should be maintained for significant alternate routes in the system. Strategic parameters are generally maintained online as five-minute running averages.

As with intersection control, historic parameters play a major role in many, if not most, freeway incident management systems. Parameters which parallel the strategic parameters are typically stored as historic files. Data are often maintained for a particular time of day and day of week for each detection station. New data are smoothed with data for the corresponding time interval of the previous week. In this way, files are maintained that represent typical time of day and day of week conditions on the highway network. These files are used for online demand estimation and are often archived for planning and design purposes. Historic parameters are typically collected in fifteen minute intervals, although five minutes and one hour intervals are also used. Some systems such as the Burlington Skyway in Ontario, Canada and the Denver, CO Freeway Traffic Management System store five minute values, but can derive fifteen minute and one-hour values upon request.

2.3.3.3 Freeway Metering Control

Table 3 contains selected parameter specifications for freeway metering control. Tactical parameters for this application include queue length estimates, demand presence, passage count, approach volume, and queue overflow presence. When a queue length is used in current applications, it is typically estimated based on approach and passage volumes or is derived from data produced by one or more presence detectors on the approach to the metering signal. Other tactical inputs to the metering control algorithm include the same mainline occupancy, speed, and flow rate used with freeway incident management.

Strategic parameters for metering include mainline and metered traffic flow rates. Mainline values are generally lane specific and include volume, occupancy, and average speeds. Derived average freeway speeds based on volume and occupancy data from a single inductive loop detector will give reasonable results for strategic decisions because collection intervals are typically five minutes or longer and smoothing procedures are normally used.

Table 2. Freeway incident detection and management traffic parameter specifications

Tactical parameters (detection)

Parameter	**Units**	**Range**	**Collection Interval**	**Allowable Error**
Mainline Flow Rate	veh/hr/lane	0-2500	20 sec	± 2.5% @ 500veh/hr/lane
Mainline Occupancy	% (by lane)	0-100	20 sec	± 1% occupancy
Mainline Speed	mph (by lane)	0-80	20 sec	± 1 mph
MainlineTravel Time	min	–	20 sec	± 5%

Strategic parameters (incident management)

Parameter	Units	Range	Collection Interval	Allowable Error
Mainline Flow Rate	veh/hr/lane	0-2500	5 min	± 2.5% @ 500veh/hr
Mainline Occupancy	%	0-100	5 min	± 2% occupancy
Mainline Speed	mph	0-80	5 min	± 1 mph
On-Ramp Flow Rate	veh/hr/lane	0-1800	5 min	± 2.5 % @ 500veh/hr/lane
Off-Ramp Flow Rate	veh/hr/lane	0-1800	5 min	± 2.5% @ 500veh/hr/lane
Link Travel Time	seconds	–	5 min	± 5%
Current O-D Patterns	veh/hr	–	5 min	± 5%

Table 2. Freeway incident detection and management traffic parameter specifications (continued)

Historic parameters (planning)

Parameter	**Units**	**Range**	**Collection Interval**	**Allowable Error**
Mainline Flow Rate	veh/hr/lane	0-2500	15 min or 1 hour	± 2.5% @ 500veh/hr/lane
Mainline Occupancy	%	0-100	15 min or 1 hour	± 2% occupancy
Mainline Speed	mph	0-80	15 min or 1 hour	± 1 mph
On-Ramp Flow Rate	veh/hr	0-1800	15 min or 1 hour	± 2.5% @ 500veh/hr
Off-RampFlow Rate	veh/hr	0-1800	15 min or 1 hour	± 2.5% @ 500veh/hr
Link Travel Times	seconds	–	15 min or 1 hour	± 5%

Current O-D Patterns	veh/hr	–	15 min or 1 hour	± 5%	

Table 3. Freeway metering control traffic parameter specifications

Tactical parameters (local responsive control)

Parameter	Units	Range	Collection Interval	Allowable Error
Ramp Demand	Yes/No	–	0.1 sec	0% (Nomissed vehicles)
Ramp Passage	Yes/No	–	0.1 sec	0% (Nomissed vehicles)
Ramp Queue Length	vehicles	0-40	20 sec	± 1vehicle
Mainline Occupancy	%	0-100	20 sec	± 2% occupancy
Mainline Flow Rate	veh/hr/lane	0-2500	20 sec	± 2.5% @ 500veh/hr/lane
Mainline Speed	mph	0-80	20 sec	± 5 mph

Strategic parameters (central control)

Parameter	Units	Range	Collection Interval	Allowable Error
Mainline Occupancy	%	0-100	5 min	± 2% occupancy
Mainline Flow Rate	veh/hr/lane	0-2500	5 min	± 2.5% @ 500veh/hr/lane
Mainline Speed	mph	0-80	5 min	± 5 mph

Historic parameters (pretimed operations)

Parameter	Units	Range	Collection Interval	Allowable Error
Mainline Occupancy	%	0-100	15 min or 1 hour	± 2% occupancy
Mainline Flow Rate	veh/hr/lane	0-2500	15 min or 1 hour	± 2.5% @ 500veh/hr/lane
Mainline Speed	mph	0-80	15 min or 1 hour	± 5 mph
On-Ramp Flow Rate	veh/hr	0-1800	15 min or 1 hour	± 2.5% @ 500veh/hr
Off-Ramp Flow Rate	veh/hr	0-1800	15 min or 1 hour	± 2.5% @ 500 veh/hr

Historic parameters of value in freeway metering include those already identified as strategic plus on-ramp and off-ramp flow rates. The collection interval for historic data is lengthened to fifteen minutes or one hour, which are the intervals used with freeway incident detection and management.

2.4 DETECTOR TECHNOLOGIES EVALUATED

The detector technologies evaluated in the field tests were ultrasonic, microwave radar, infrared laser radar, nonimaging passive infrared, video image processing using visible spectrum and infrared imagery, passive acoustic array, high sampling rate inductive loop, conventional inductive loop, microloop, and magnetometer as shown in Table 4. The term passive denotes that energy is not transmitted by the detector as these devices sense energy or signals emitted by the vehicles and roadway. The theory of operation of each of the technologies has appeared in project reports and other papers.1,5,6 Weigh-in-motion types of detectors were not part of the study.

The cold winter environment evaluations of detector performance were conducted in Minnesota; summer thunderstorms, lightning, and humidity were experienced in Florida; and dry desert summer heat in Arizona. Testing in Minnesota occurred during winter 1993, in Florida during summer of 1993, and in Arizona during fall and winter of 1993 and summer of 1994. Some results have previously been reported.7,8,9,10 Desired IVHS traffic parameter and accuracy specifications, manufacturers detector specifications,11 laboratory detector test specifications and test plans,12 and laboratory test results13 are described in detail in the project reports. These will be made available electronically from a bulletin board maintained by FHWA.

2.5 TEST SITE DESCRIPTION

The testing period, weather, traffic flow direction, and quantity of data collected at each site are listed in Table 5. The large volume of data gathered in Tucson was due to the larger number of detectors that were evaluated at this site. These included detectors that were not available at the other sites, such as a high sampling rate inductive loop detector amplifier, an array of six three-axis fluxgate magnetometers deployed across the roadway, an infrared video image processor, a pair of six-foot diameter round inductive loops, and microloop detectors. Data from several of these detectors may be useful for vehicle classification and link travel time calculation.

At most sites, the overhead detectors were mounted on 1-1/2 inch (3.8 cm)galvanized iron pipe that itself was attached to an overhead structure such as an overpass, sign support, or traffic signal mast arm. An example of overhead detector mounting on a sign support structure is shown in Figure 2 for the Minneapolis Minnesota surface street site. Figure 3 provides a key to the location of the various detector models on the structure. Figures 4 and 5, representing a typical freeway configuration, show the overhead detector mounting used at Altamonte Springs Florida (near Orlando). At the Phoenix Arizona freeway site, the overhead detectors were mounted directly to a sign bridge that spanned the freeway as shown in Figure 6. The Tucson Arizona site, in Figures 7 and 8, illustrates the mast arm mounting used at the Florida and Tucson surface street evaluation sites. Figure 9 (representing Tucson) is typical of the drawings used to document the location of the in-ground detectors at surface street sites.

Side-looking detectors were mounted on either existing light poles and overpass support structures or on wooden poles that were added on the shoulders of the road. Pairs of 6-foot (1.8 m) square inductive loop detectors, with 15 feet (4.6 m) nominal center-to-center spacing, were placed under the road surface in the monitored traffic lanes. The self-powered magnetometers were installed in the middle of the square loops in one of the lanes. The onset and duration of the green phase signal at surface street sites were recorded to correlate with the traffic data. Distance from the overhead sensor mounting location was painted on the road surface to support video image processor (VIP) calibration. The areas viewed by the video cameras, the approximate areas illuminated by the overhead detectors, and the position of the in-ground detectors were documented as shown in Figures 10 and 11, representing the Phoenix freeway site.

Table 4. Detectors evaluated during field tests

Symbol	Technology	Manufacturer	Model
U-1	Ultrasonic Doppler	Sumitomo	SDU-200 (RDU-101)
U-2	Ultrasonic Presence	Sumitomo	SDU-300
U-3	Ultrasonic Presence	Microwave Sensors	TC-30C
M-1	Microwave Radar Motion Medium Beamwidth	Microwave Sensors	TC-20
M-2	Microwave Radar Doppler Medium Beamwidth	Microwave Sensors	TC-26
M-4*	Microwave Radar Doppler Narrow Beamwidth	Whelen	TDN-30
M-5	Microwave Radar Doppler Wide Beamwidth	Whelen	TDW-10
M-6	Microwave Radar Presence Narrow Beamwidth	Electronic Integrated Systems	RTMS-X1
IR-1	Active IR Laser Radar	Schwartz Electro-Optics	780D1000 (Autosense I)
IR-2	Passive IR Presence	Eltec	842
IR-3	Passive IR Pulse Output	Eltec	833
IIR-1**	Imaging IR	Northrop-Grumman	Traffic Sensor
VIP-1	Video Image Processor	Econolite	Autoscope 2003
VIP-2	Video Image Processor	Computer Recognition Systems	Traffic Analysis System
VIP-3***	Video Image Processor	Traficon	CCATS-VIP 2
VIP-4**	Video Image Processor	Sumitomo	IDET-100
VIP-5+	Video Image Processor	EVA	2000
A-1++	Passive Acoustic Array	AT&T	SmartSonic TSS-1
MA-1	Magnetometer	Midian Electronics	Self Powered Vehicle Detector
L-1**	Microloop	3M	701

T-1**	Tube-Type Vehicle Counter	Timemark	Delta 1

* M-3 was reserved for a microwave detector not available for evaluation in this program.

** Used at Tucson Arizona test site only. *** Used at all Arizona test sites.+ Used in Phoenix Arizona 7/94 test only. ++ Used in Phoenix 11/93 and Tucson tests.**Table 5. Evaluation site weather, traffic flow direction, and quantity of data acquired**

Location	Test Period and Weather	Runs	Data Collected (MBytes)	Traffic Flow Direction
Minneapolis Freeway I-394 at Penn Ave.	Winter 1993	15	200	Departing (AM); Departing and approaching (PM)
Minneapolis Surface Street Olson Hwy. at Lyndale Ave.	Cold, snow, sleet, fog	7	32	Departing
Orlando Freeway I-4 at SR 436	Summer 1993	28	670	Approaching
Orlando surface street SR 436 at I-4	Hot, humid, heavy rain, lightning	21	200	Departing
Phoenix freeway I-10 at 13th Street	Autumn 1993 Warm, rain	32	868	Approaching
Tucson surface street Oracle Rd. at Auto Mall Dr.	Winter 1994 Warm	34	2892	Departing
Phoenix freeway I-10 at 13th Street	Summer 1994 Hot, low humidity, some rain	31	1060	Approaching

Further descriptions of the test locations are found in the Task B Report, Task L Final Report, and other papers.[7,8,9,14,15] The detailed field test plan is contained in the Task F Report.[5]

2.6 RECORDING OF TRAFFIC FLOW DATA

A data logger was designed and built to time tag and record the detector output data. Recorded data consisted of vehicle count, presence, occupancy, speed, and classification based on vehicle length, depending on the information supplied by a particular detector. The detector outputs were recorded directly onto 88 Mbyte Syquest cartridges, with the exception of the three-axis magnetometer data from the Tucson site that was recorded on a Metrum tape recorder. Preprocessing of the data before recording was not performed to avoid contaminating the raw data and losing the information.

Some detectors output both discrete and serial (RS-232) traffic parameter data, while others output only discrete data using Form-C relays or optically-isolated semiconductors. Up to sixteen serial detector outputs, forty optically-isolated outputs, sixteen Form-C relay closure outputs, and eight analog outputs that include environmental data (e.g., temperature, wind speed, wind direction) and analog detector outputs such as Doppler frequency could be recorded. The data logger and other equipment were housed in a trailer located alongside the roadway test site.

2.7 DATA ACQUISITION RUNS

Data acquisition runs included morning rush hours with darkness to daylight lighting transitions and evening rush hours with daylight to darkness lighting transitions. During most runs, a probe vehicle was driven through the field of view of the detectors at a known speed to aid in the calibration of the detectors' speed outputs. In Phoenix and Tucson, the identification of the probe vehicle was aided by a bumper-mounted transducer that transmitted an identification code through the loop to the data logger. Traffic parameter truth data such as counts and vehicle type

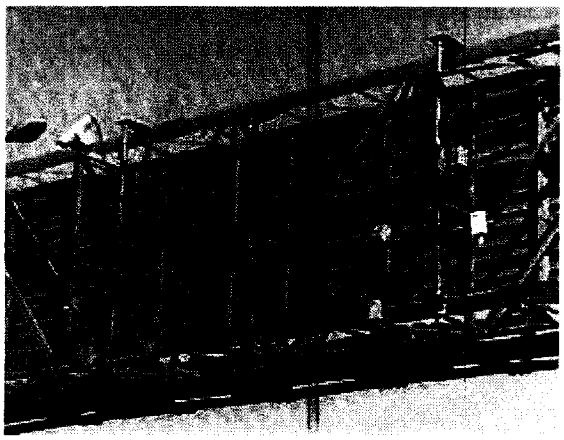


Figure 2. Overhead-mounted detectors above Olson Highway westbound lanes in Minneapolis, MN

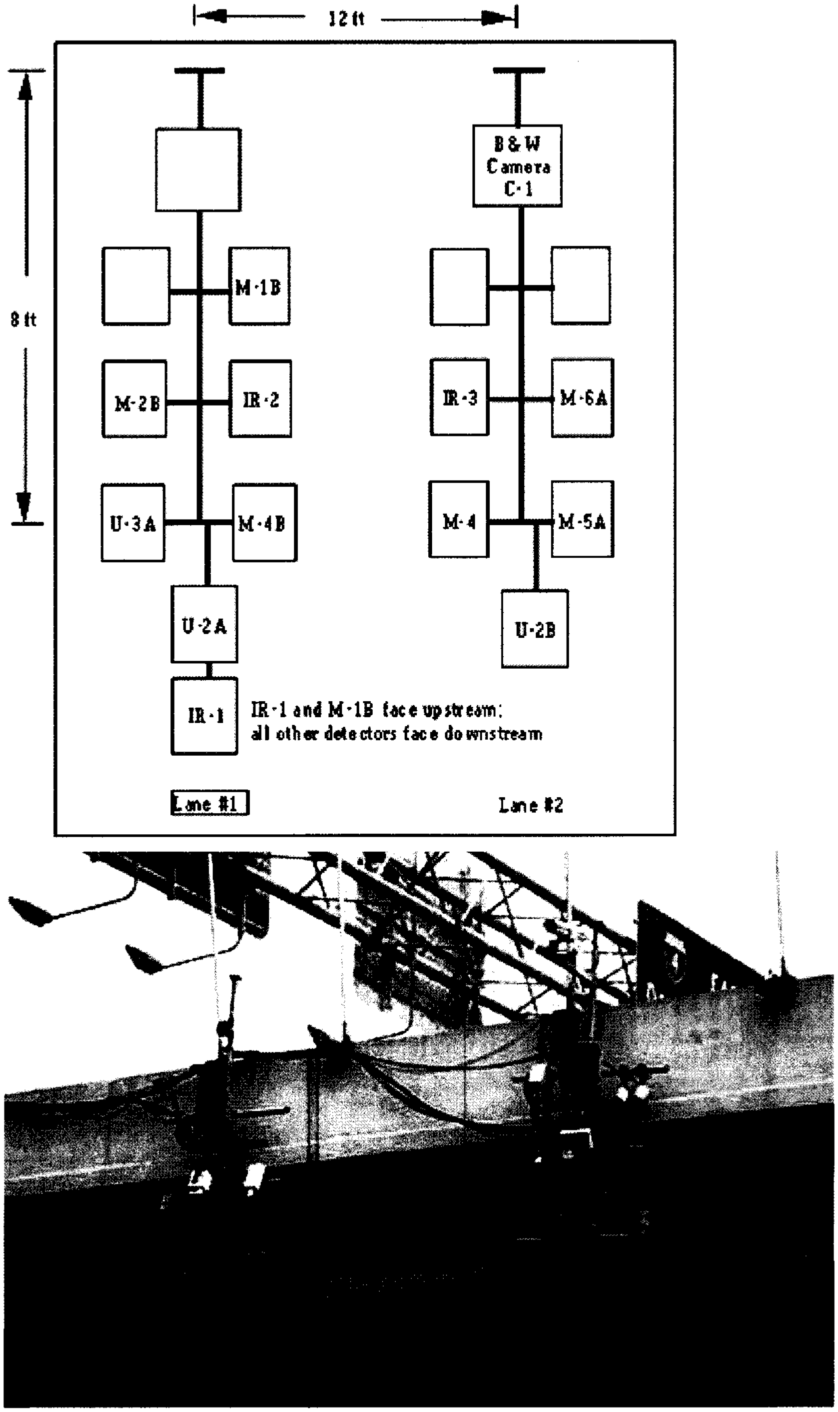


Figure 4. Overhead-mounted detectors above I-4 freeway westbound lanes near Orlando, FL

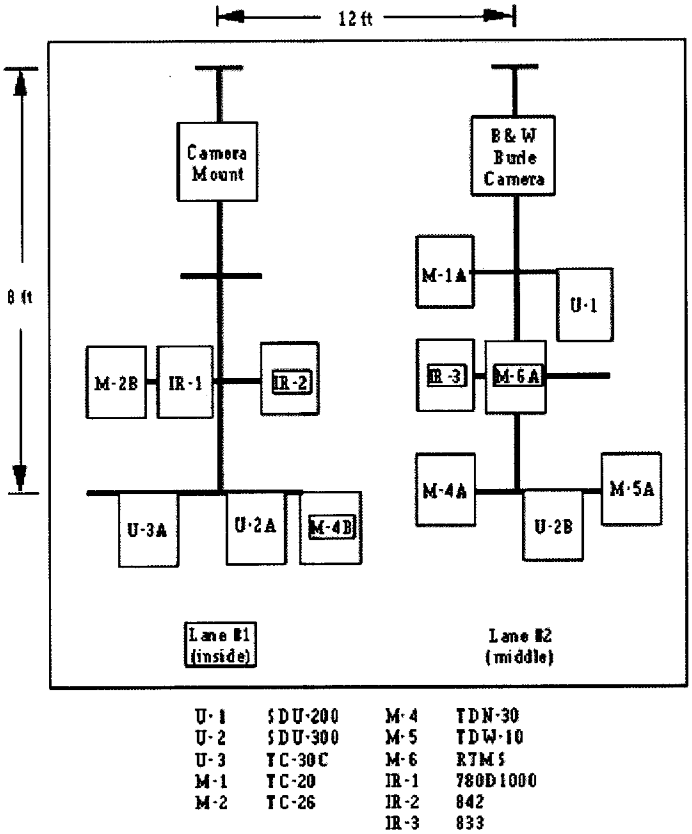


Figure 5. Overhead detector layout at I-4 freeway site

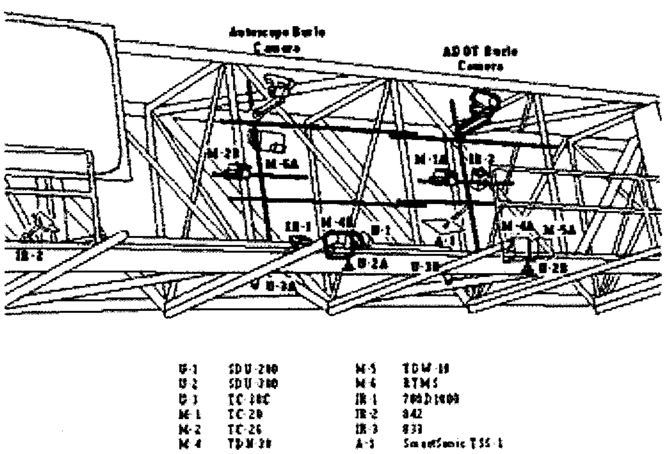


Figure 6. Overhead detector layout used at I-10 freeway in Phoenix, AZ

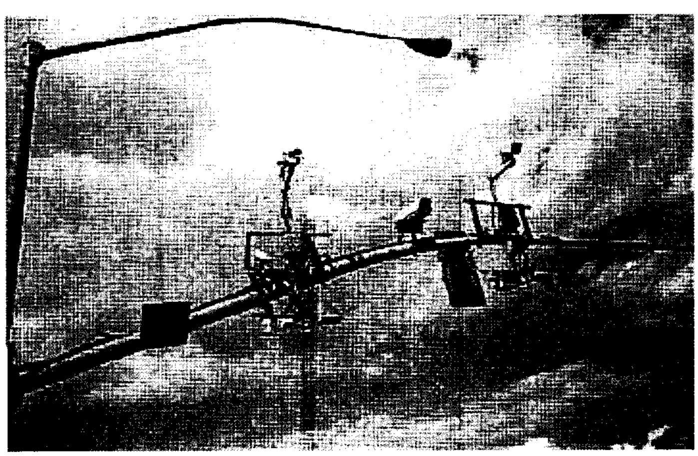


Figure 7. Detectors over southbound lanes at Oracle Road surface street site in Tucson, AZ

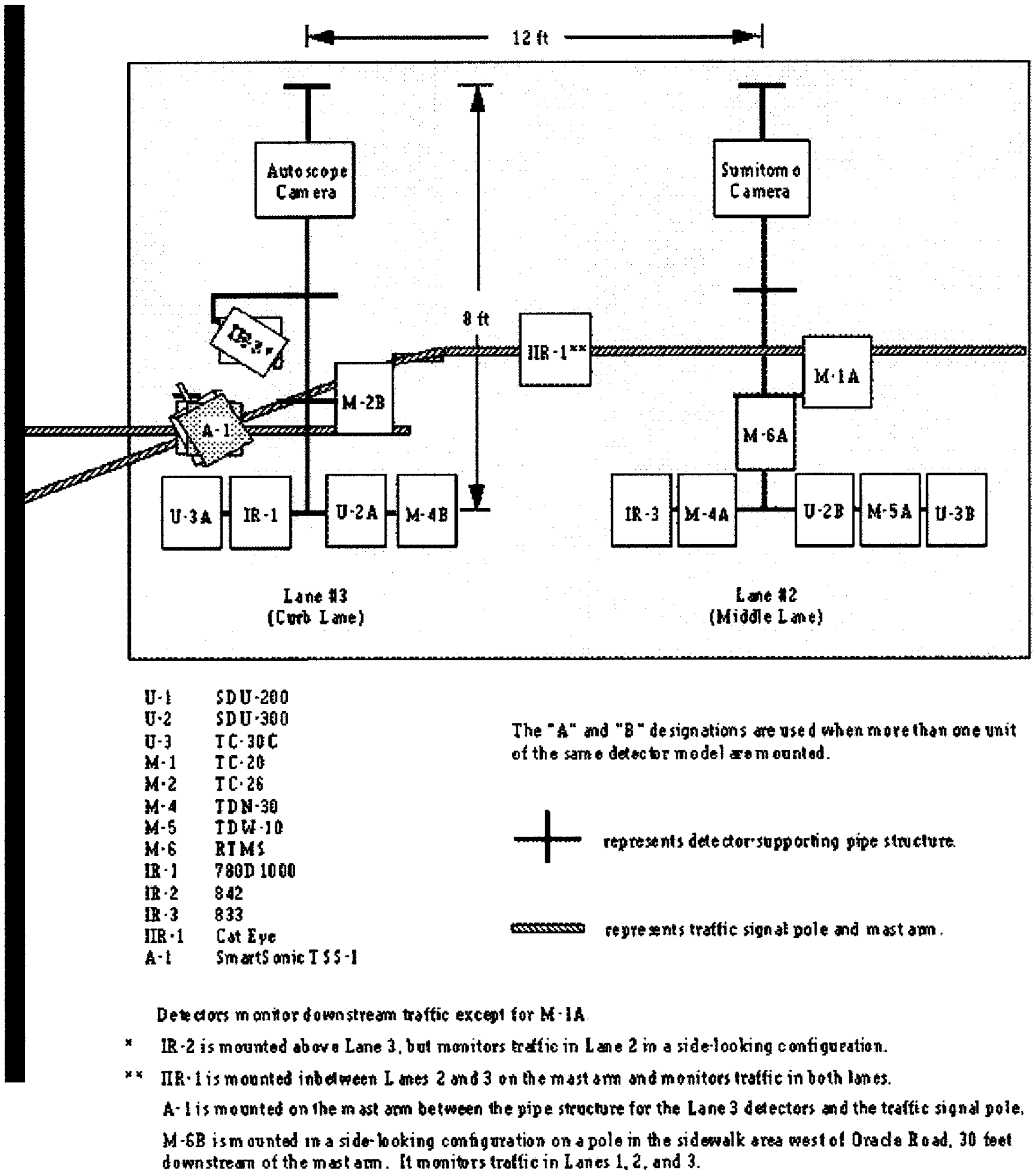
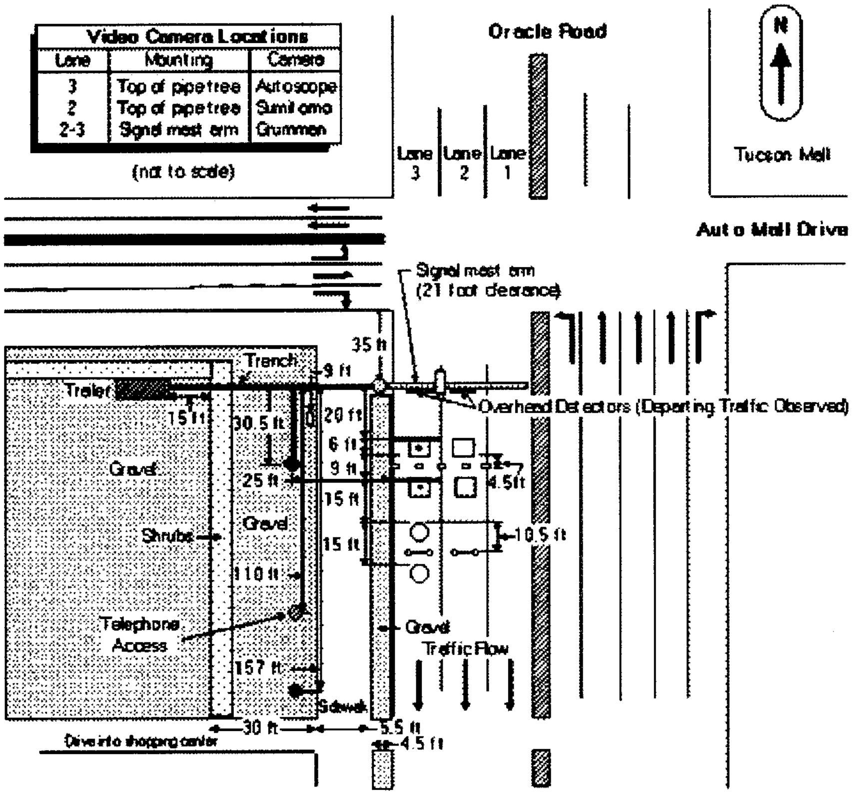


Figure 8. Overhead detector array as used at Oracle Road surface street site in Tucson, AZ



- □ 6-ft x 6-ft square inductive loop detector
- ○ 6-ft diameter round inductive loop detector
- • Self powered vehicle detector (SPVD) with built in RF data link (requires 6-in x 22-in hole)
- ▫ 3-axis fluxgate magnetometer (requires 6-in x 20-in hole)
- ⟜ 3M microloops
- ▬ Tube-type vehicle counter
- ● 15-foot pole for mounting side-looking detectors (at least 4-in x 4-in cross section)
- ⊘ Electric utility pole
- ⊗ Street light pole
- ▯ Controller cabinet

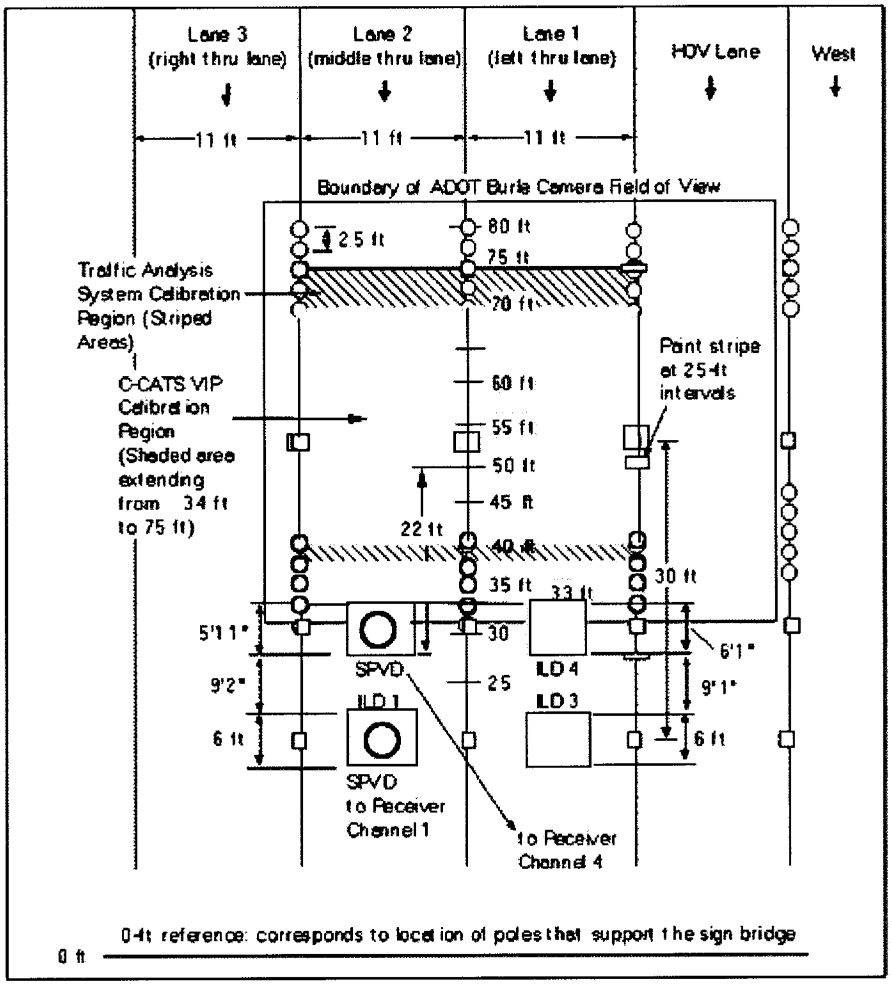
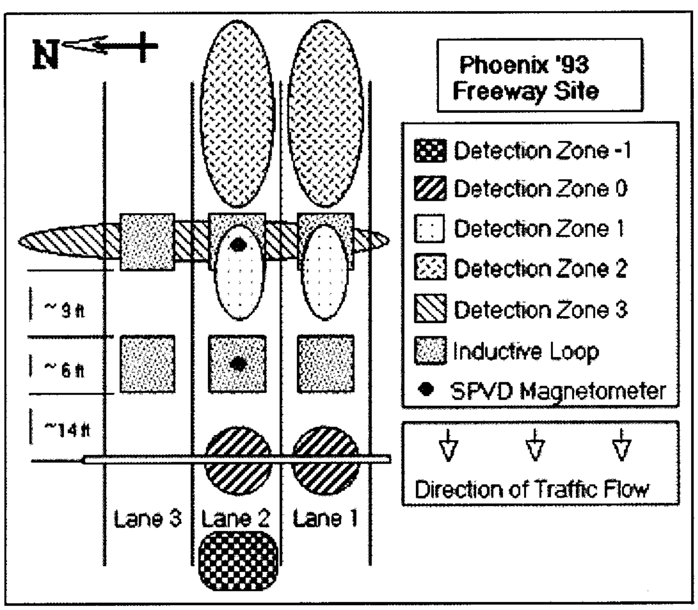


Figure 10. Location of inductive loop detectors, self-powered magnetometers, Traffic Analysis System and CCATS video image processor calibration regions, and ADOT Burle camera field of view on I-10 freeway during Autumn 1993 detector technology evaluations were obtained from the recorded video imagery.



1 ft = 0.305 m

Zone	Lane 1		Lane 2		Lane 3	
	Symbol	Model	Symbol	Model	Symbol	Model
-1			A1 IR3	AT&T Acoustic Array Eltec 833		
0	U3A U2A IL1A-2 IR1 IR2	MW Sensors TC-30C Sumitomo SDU-300 Inductive Loop Schwartz 780D1000 Eltec 842	U3B U2B IL1B-2 MG2A-2	MW Sensors TC-30C Sumitomo SDU-300 Inductive Loop SPVD Magnetometer	IL1C-2	Inductive Loop
1	IL1A-1 M4B M2B M6A-3 U1	Inductive Loop Whelen TDN-30 MW Sensors TC-26 EIS RTMS (fwd-look) Sumitomo RDU-101	IL1B-1 M4A M1A MG2A-1	Inductive Loop Whelen TDN-30 MW Sensors TC-20 SPVD Magnetometer	IL1C-1	Inductive Loop
2	VP1C M6A-2	Autoscope 2003 VIP EIS RTMS (fwd-look)	VP1B M5A	Autoscope 2003 VIP Whelen TDW-10	VP1A	Autoscope 2003 VIP
3	M6A-5	EIS RTMS (side-look)	M6A-6	EIS RTMS (side-look)	M6A-7	EIS RTMS (side-look

Figure 11. Detection zones on I-10 freeway in Phoenix, AZ during Autumn 1993 detector technology evaluations2.8 DATA ANALYSIS

The recorded discrete and serial detector data were converted into a comma-delimited format that was compatible with importation into a database program. The data were then read into an easily accessible database using Windows-based Paradox software. In this form, the original recorded data volume was compressed by approximately a factor of two. Selected files were tagged by detector technology, time of run, weather, or data type for further analysis in a program such as Mathcad or with specially written FORTRAN code. Similar parameters from several detectors were plotted as a function of time of day or another independent variable. Selected detector outputs or analysis results, such as detector technology type, traffic parameters (e.g., count, speed, occupancy), and mean and standard deviation of the traffic data parameter, can also be superimposed onto the video imagery recorded during the data collection process to facilitate a qualitative comparison of technology performance.[6] The Paradox files will be made available on CD-ROM discs.

2.9 RESULTS

Traffic volume reported by the detectors was compared with volumes established by counting vehicles in the recorded video imagery from several runs. At least two hours of data were manually counted for each test site. The number of runs subjected to this ground truth procedure was increased during subsequent data analysis of all of the runs that will be reported in an addendum to the final report. It was found that the loops at all sites but one gave counts that were usually within 0.5% of the manual counts obtained from the recorded imagery and, thus, the automated loop counts were typically used as reference values against which to compare the counts from other detectors.8 The exception was the Phoenix freeway site where cross talk between loops in the same lane was present. This problem was isolated to the loop wire installation, but no further specific cause for the crosstalk was able to be determined.

There were other instances as well where counts from a detector other than an inductive loop appeared to be closer to the manual count for a particular run or a particular site. In these instances, the automated count from the other detector was used as the standard against which to compare the counts from the rest of the detectors in the run. The manual ground truth value or the automated detector count used as the standard is always referenced in the figure that displays the data. Percent difference is used to denote the variation between data from a given detector and a loop or other detector used as the standard, while percent error denotes the difference between data from a detector and the ground truth value. Run designations are in the form *MMDDhhmm*, where *MM* represents the month, *DD* the day of the month, *hh* the hour in which the run began, and *mm* the minute at which the run began.